HELIO SWARM

THE NATURE OF TURBULENCE IN SPACE PLASMAS

Mission Operations Introduction & Development Approach

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Who Are We?

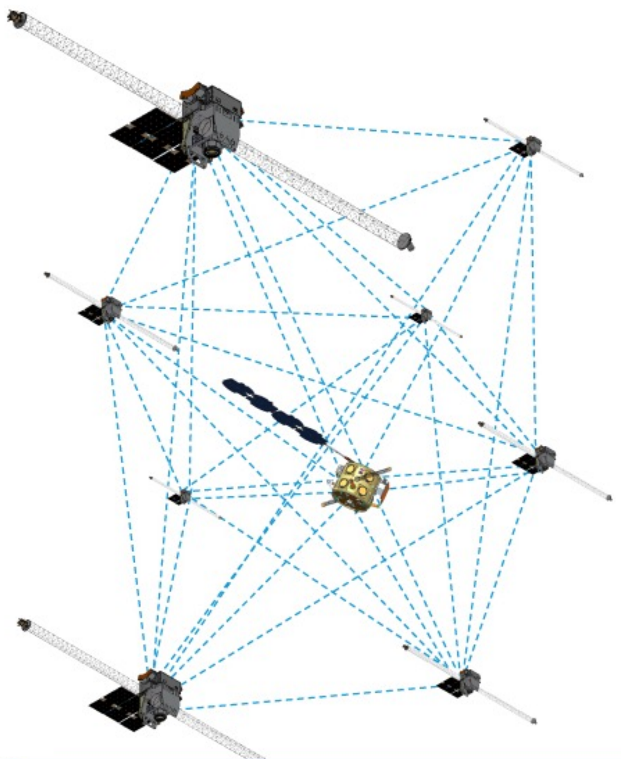
Matthew D’Ortenzio, NASA Ames

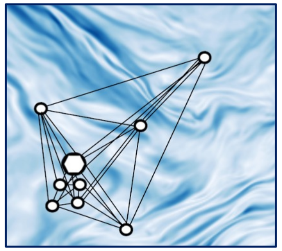
Mission operations manager for LADEE, STPSat-5, and BioSentinel (interim). Lead flight controller and DSN interface for LCROSS. Currently mission ops development staff for HelioSwarm and ORT lead for Starling-1.

John Bresina PhD, NASA Ames

Mission Planning & Sequencing lead for LADEE and LCROSS, and support for MER and MSL. Research Scientist with over 25 years of NASA R&D experience in AI planning, scheduling and execution. Currently mission ops development staff for HelioSwarm and project manager for Après mission planning software.

Agenda

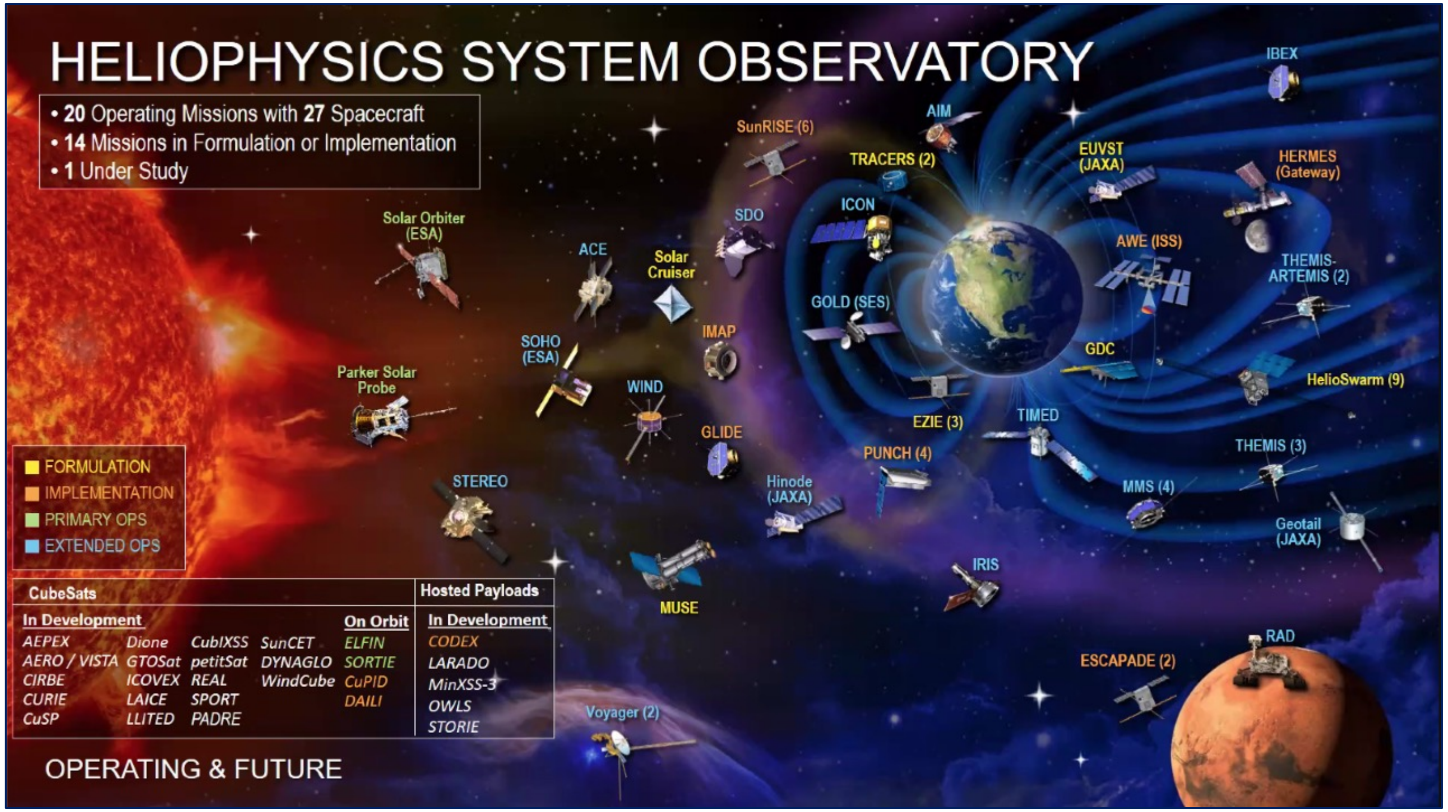




- **HelioSwarm Introduction**
- **Mission Overview**
  - **Science Investigation**
  - **Mission design**
- **Mission Operations & Ground Systems Overview and Approach**
- **Questions & Discussion**

The Basics

- NASA Science Mission Directorate (SMD) Explorers Program competed mission
- Heliophysics Medium-Sized Explorer class (aka “MIDEX”)
- PI Mission Cost Cap: $250M
- Timeline:
  - Step-1 Proposal: Sep. 2019
  - Step-2 Proposal: Jul. 2021
  - Site Visit: Nov. 2021
  - Selection: Feb. 2022
  - Launch: Q1 2029
  - Operations: 18 months
    (12 months of Science)



Participating Organizations

HELIO SWARM

Primary Investigator:

Harlan Spence PhD, University of New Hampshire

Deputy PI:

Kristopher Klein PhD, University of Arizona

Project Manager:

Butler Hine PhD, NASA Ames

Project Systems Engineer:

Brittany Wickizer, NASA Ames

University of New Hampshire
Ames Research Center
Goddard SPACE FLIGHT CENTER
NORTHROP GRUMMAN
BLUE CANYON TECHNOLOGIES
Smithsonian
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE
THE UNIVERSITY OF ARIZONA
Berkeley UNIVERSITY OF CALIFORNIA
BWXT
THE UNIVERSITY OF CHICAGO
UNIVERSITY OF DELAWARE
IOWA
Los Alamos NATIONAL LABORATORY
PRINCETON UNIVERSITY
WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

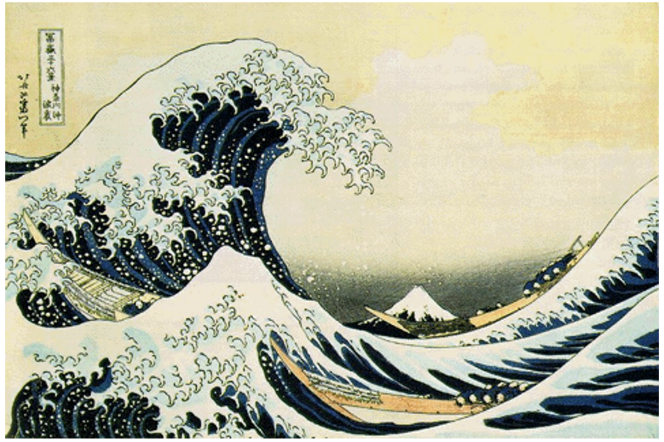
LPP
Imperial College London
irap astrophysique & planétologie
LPC2E
UCL
UNIVERSITY OF OXFORD
l'Observatoire de Paris — LESIA
Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique
UNIVERSITY OF CAMBRIDGE
ÖAW AUSTRIAN ACADEMY OF SCIENCES

HelioSwarm: The Nature of Turbulence in Space Plasmas

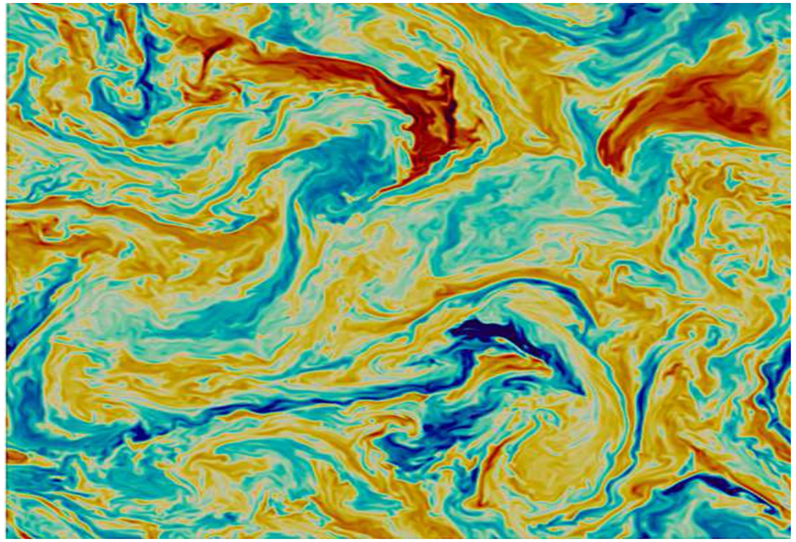
Turbulence is Multiscale Disorder

- Turbulent flow is one in which a gas, fluid, or plasma undergoes irregular fluctuations and mixing
- Turbulent flows are multiscale; energy injected at largest size scale cascades to smaller scales, eventually converting the kinetic energy in the flow into thermal energy of the constituent medium
- Turbulence is considered by many to be the last unsolved mystery of classical physics

Turbulence plays a fundamental role driving the transport of mass, momentum, and energy in a wide variety of kinds of plasmas



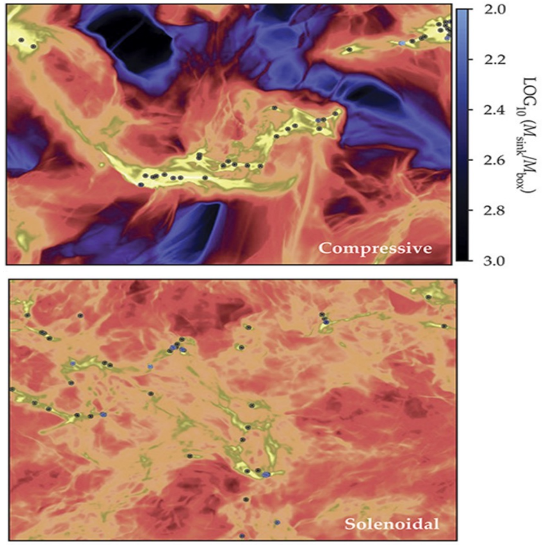
Katsushika Hokusai,
Thirty-six views of Mt. Fuji.



Meyrand et al 2019

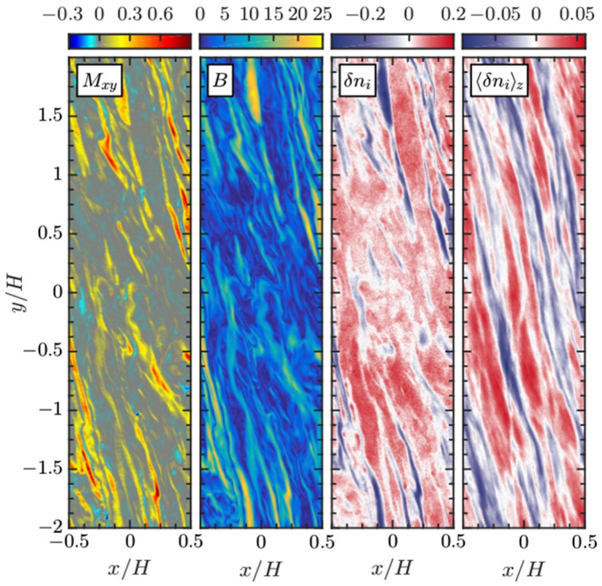
Turbulence Plays a Fundamental Role in Universal Plasmas

Star Formation



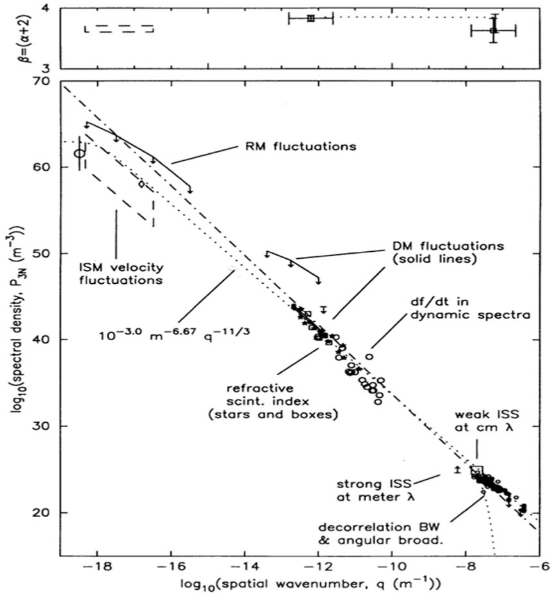
Star Formation Simulations
(Federrath & Klessen 2012)

Black Hole Accretion Disks



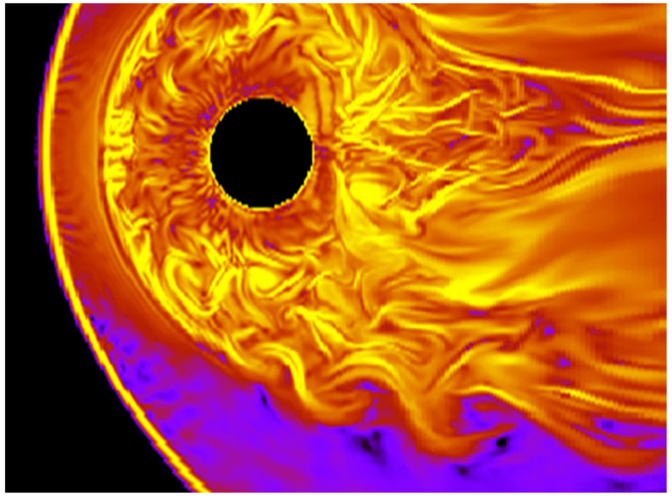
MRI Turbulence Simulations
(Kunz et al 2016)

Interstellar Medium (ISM)



ISM Observations
(Armstrong et al 1995)

Solar Wind / Earth's Magnetosphere



OpenGGCM MHD simulation of Earth's magnetosphere, S. Kavosi, J. Raeder

HelioSwarm Goals and Objectives

Science

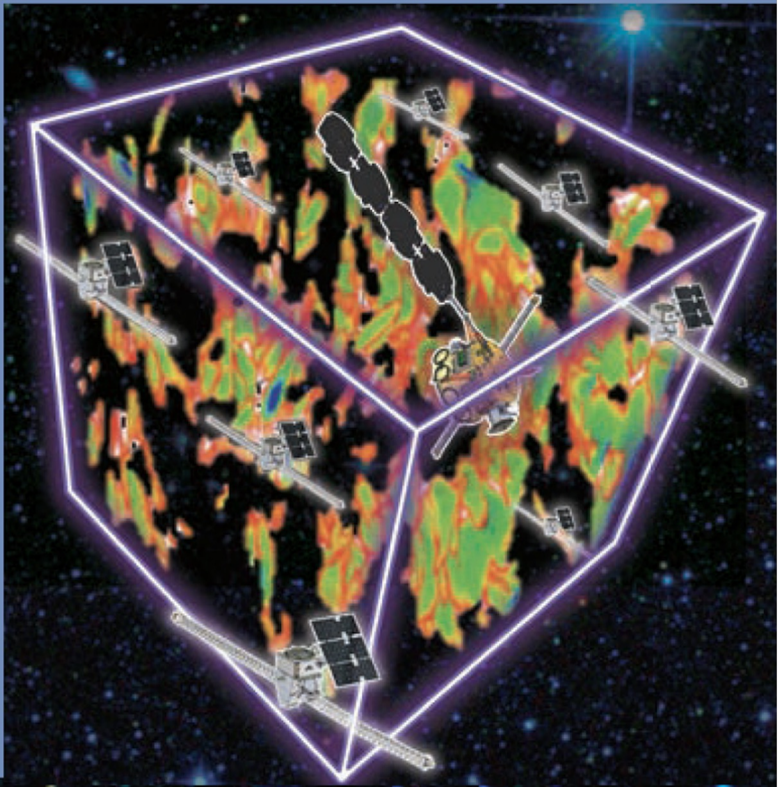
HelioSwarm science is tightly aligned with NAS 2013 Heliophysics Decadal Survey and NASA SMD Priorities: Turbulence identified as a Decadal Science Goal ("Understand the origins and effects of turbulence") and a Decadal Imperative ("Implement . . . a multispacecraft mission to address cross-scale plasma physics")

Goal #1: Reveal the 3D spatial structure and dynamics of turbulence in a weakly collisional plasma.

- O1: Reveal how turbulent energy is transferred in most probable,undisturbed solar wind plasma and distributed as a function of scale and time.
- O2: Reveal how turbulent cascade of energy varies with background magnetic field and plasma parameters in different environments.
- O3: Quantify transfer of turbulent energy between fields, flows, and protons.
- O4: Identify thermodynamic impacts of intermittent structures on proton distributions.

Goal #2: Ascertain the mutual impact of turbulence near boundaries and large-scale structures.

- O1: Determine how solar wind turbulence affects and is affected by large-scale structures.
- O2: Determine how strongly driven turbulence in the foreshock, magnetosheath, and magnetosphere differs from that in the undisturbed solar wind.



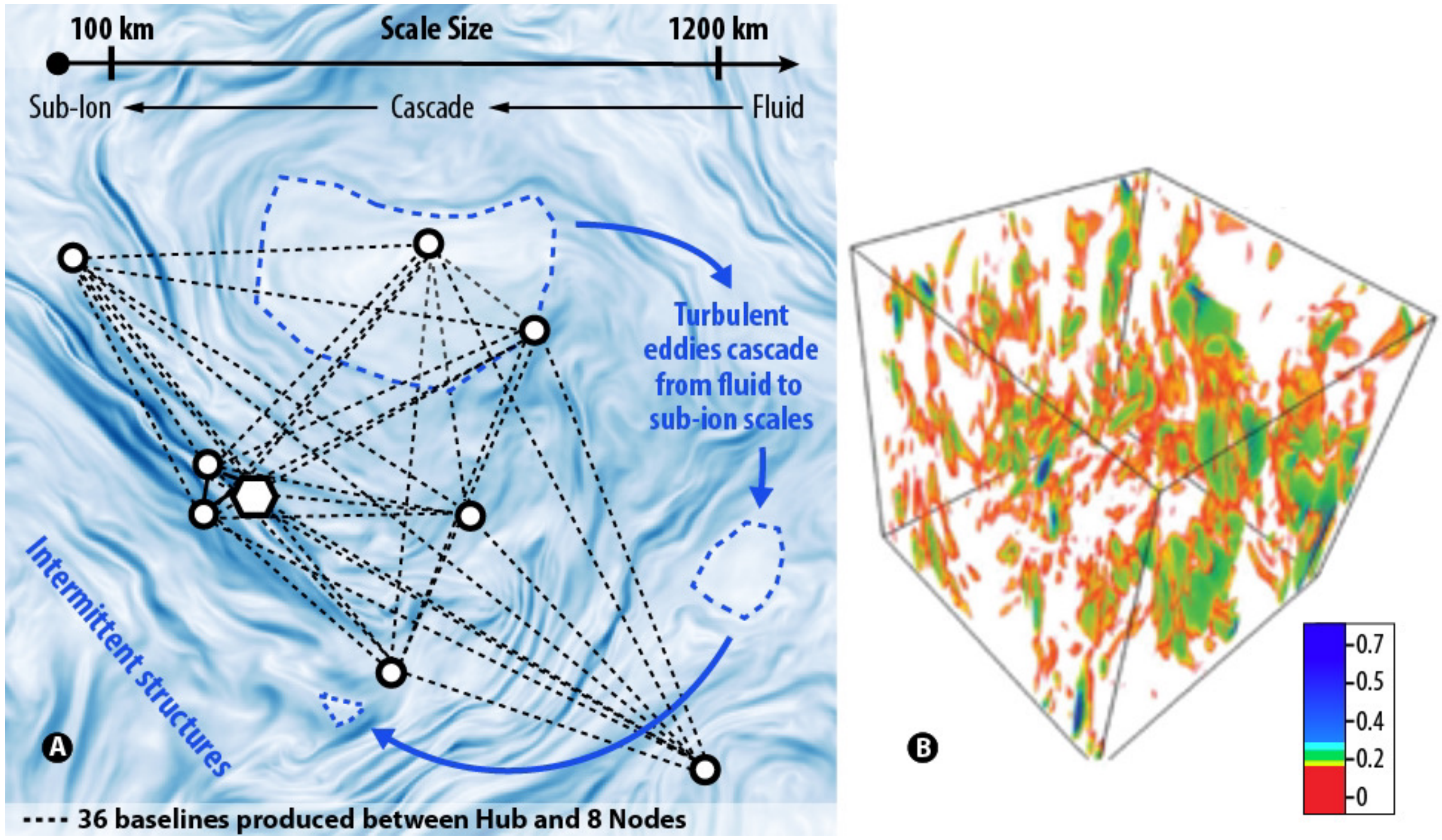
HelioSwarm's first-ever simultaneous multipoint, multiscale measurements disentangle spatial and temporal variations in solar wind plasmas that connect MHD scale turbulence with sub-ion scale heating.

Overcoming Previous Limitations

- Single S/C observations (Wind, ACE, IMAP, etc.) are fundamentally limited w.r.t. turbulence characterization

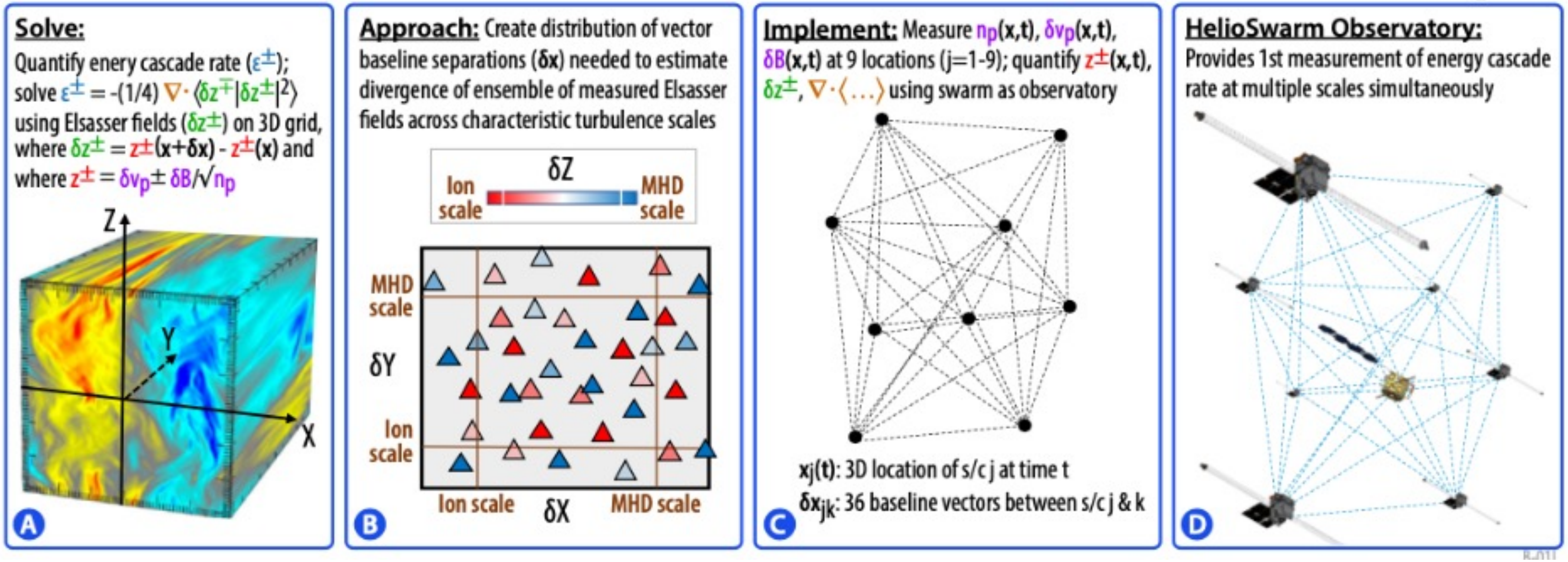
- Multi-S/C missions (Cluster, MMS, THEMIS) provide single-scale observations

- Science questions require multi-point and simultaneous multi-scale measurements
  - MHD (>1200 km)
  - Transition (> 100 km, < 1200 km)
  - Sub-ion (< 100 km)



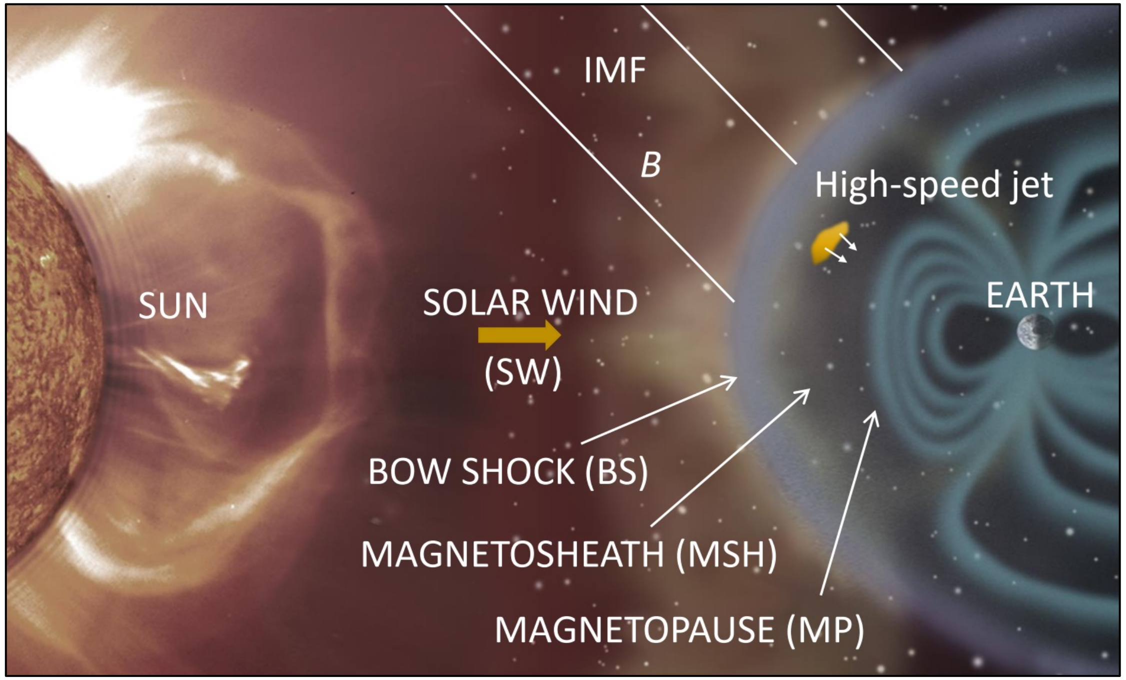
Observation Approach

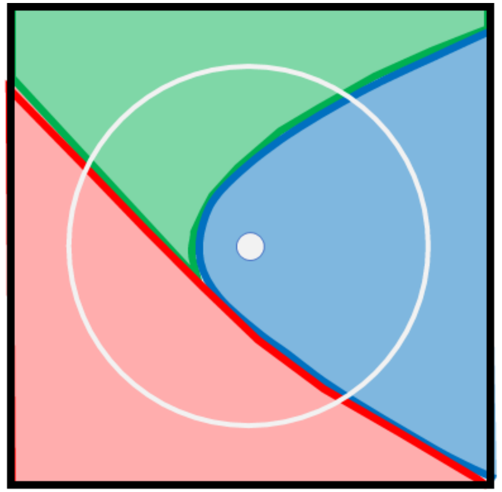
HelioSwarm overcomes the limitations of approximations central to using data from single-spacecraft or single-scale missions, providing a complete space-time measurement of the underlying turbulent dynamics from fluid to ion scales in a variety of near-Earth plasma environments



HelioSwarm's Laboratory

- The solar wind and its interaction with Earth's magnetosphere provide an ideal laboratory for the study of space plasma turbulence
- Measurement regions:
  - Pristine Solar Wind
  - Strongly Driven Turbulent Regions (foreshock, magnetosheath, and magnetosphere)

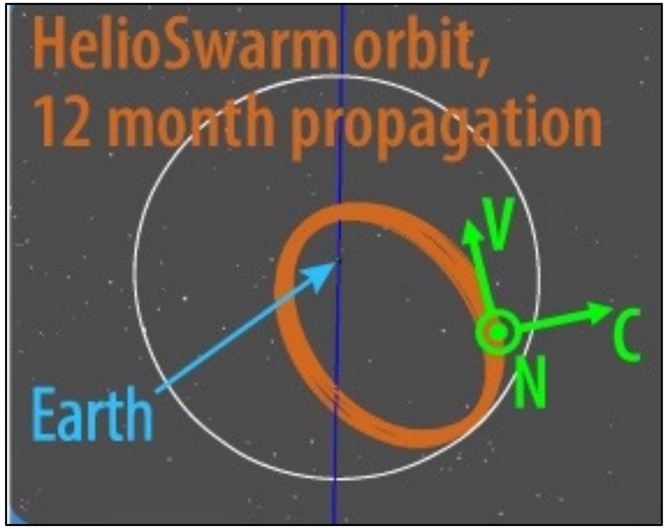




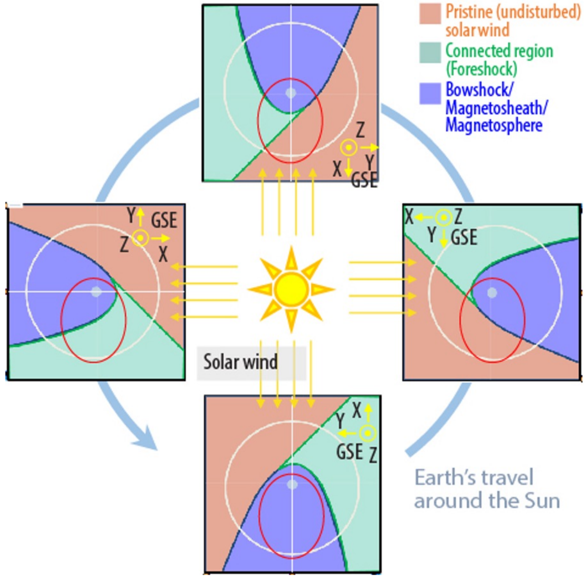
Pristine solar wind
Connected Region (Foreshock)
Bowshock / Magnetosheath / Magnetosphere
Lunar Orbit

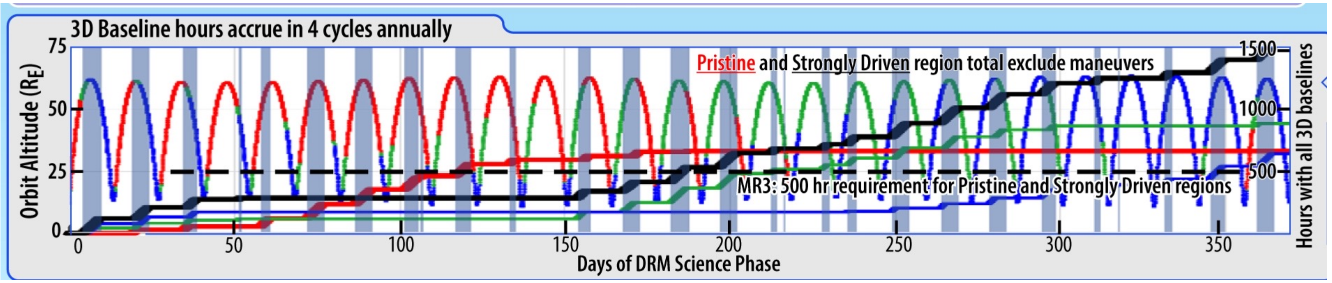
HelioSwarm Science Orbit

- Highly elliptical Earth Orbit
  - Perigee: 10 - 15 R_E
  - Apogee: 60 - 65 R_E
  - 15-degree inclination
- P/2 Lunar Resonant (14-day period)
- No maintenance required once established



- Inertially fixed orbit; orientation of orbit relative to Sun-Earth geometric slowly rotates over 12-month science phase





HelioSwarm Instrument Suite

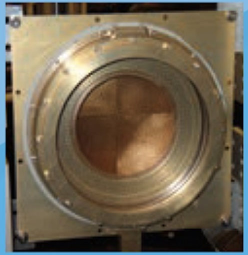
Science Instruments
High-TRL, high-heritage instrument suite optimized for solar wind turbulence measurements.

HUB & NODE

Fluxgate Magnetometer (FGM)
- Vector DC magnetic fields
- Solar Orbiter post-environmental heritage and JUICE design heritage

Search Coil Magnetometer (SCM)
- Vector AC magnetic fields
- JUICE design heritage

Faraday Cup (FC)
- Solar wind plasma density and velocity
- Parker Solar Probe, WIND, DSCOVR flight heritage



HUB ONLY

Ion Electrostatic Analyzer (iESA)
- Ion velocity distributions
- Solar Orbiter post-environmental heritage and MAVEN flight heritage

Tim Horbury (Lead)

Imperial College London

Olivier Le Contel (Lead)

LPP/CNES

Tony Case (Lead)

Smithsonian Astrophysical Observatory

Benoit Lavraud (Lead)

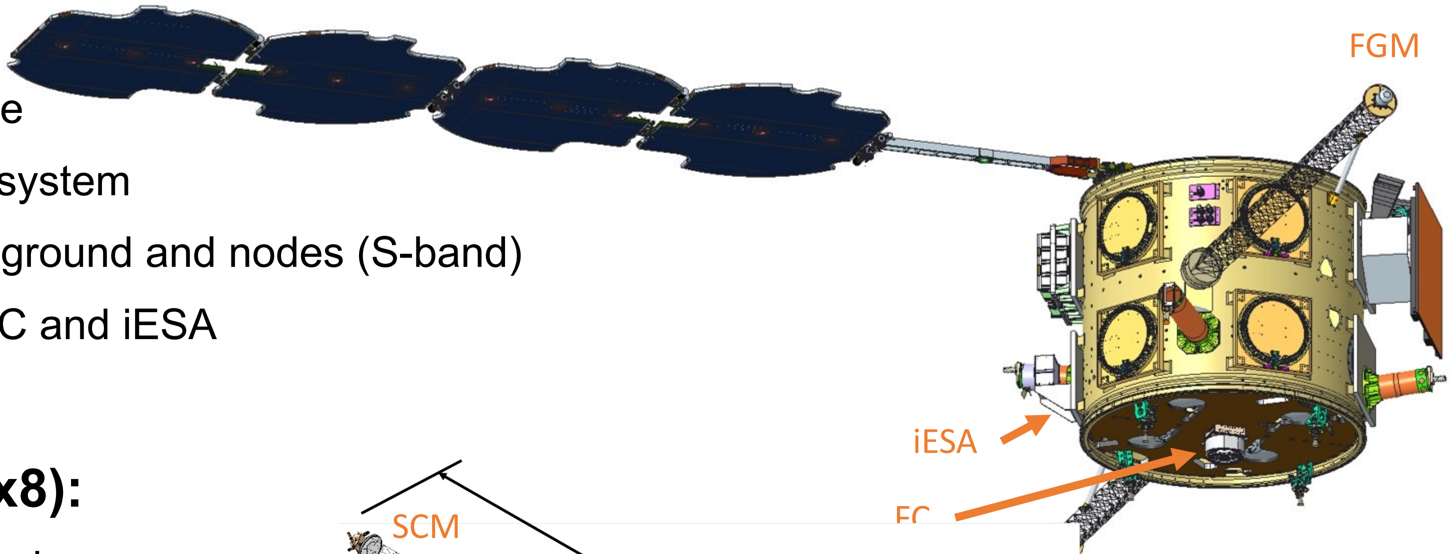
IRAP/CNRS

An Electron ESA, lead by Phyllis Whittlesey (UC Berkeley), is included as a Student Collaboration Option for installation on the Hub

HelioSwarm Spacecrafts

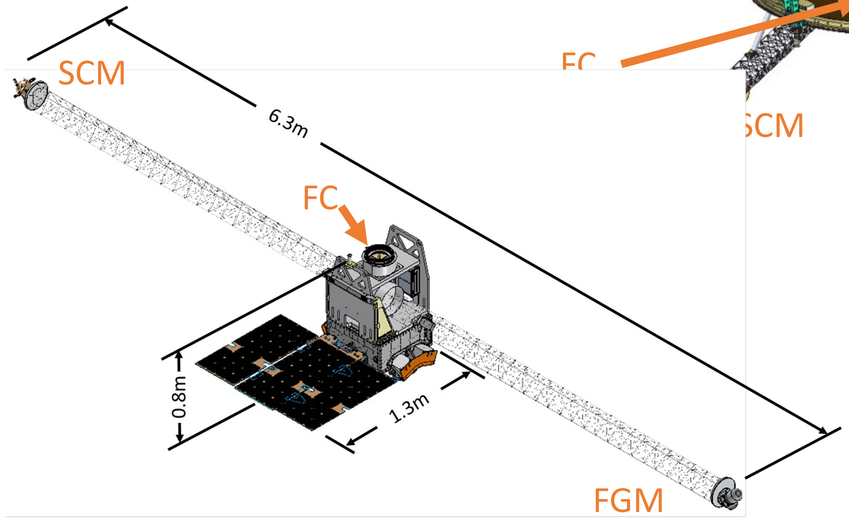
Hub Spacecraft (x1):

- Northrop Grumman
- ESPAStar Product Line
- Hydrazine propulsion system
- Communications with ground and nodes (S-band)
- Carries SCM, FGM, FC and iESA

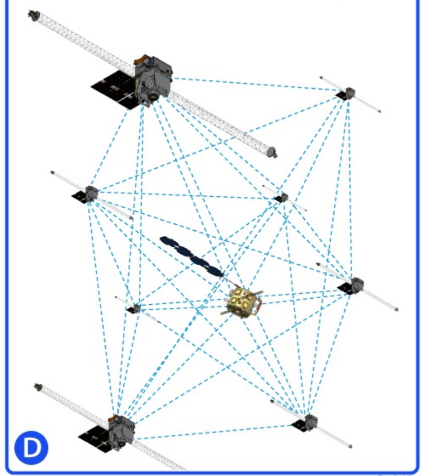


Node Spacecraft (x8):

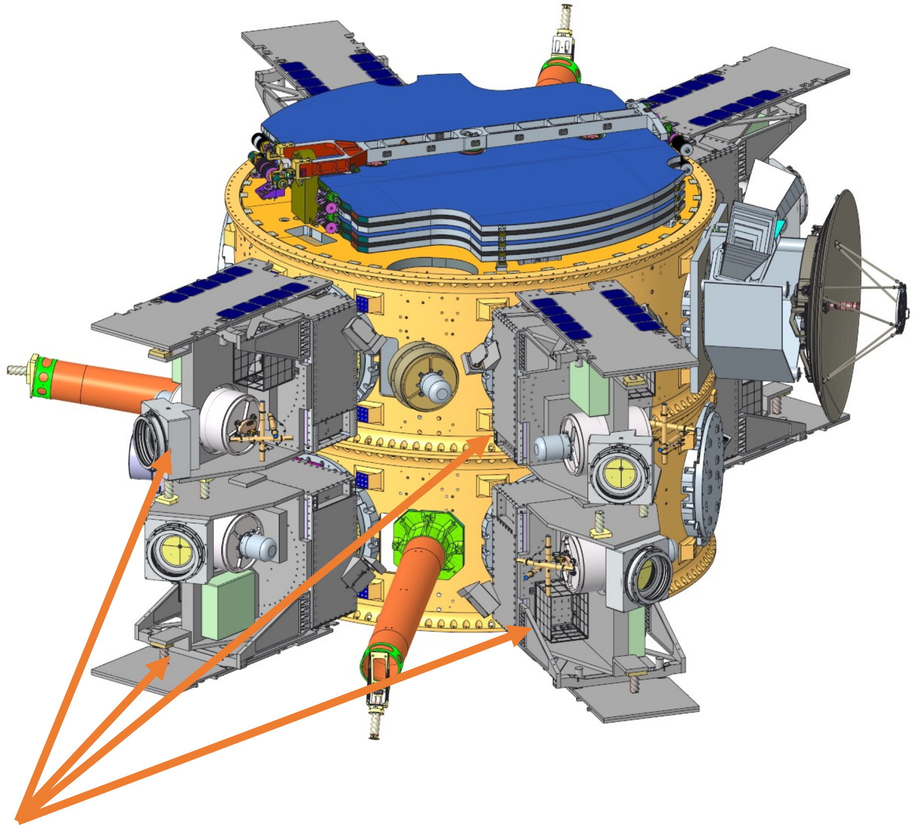
- Blue Canyon Technologies
- Venus Bus Product Line
- Low-thrust ion propulsion system
- Communication with hub only (S-band)
- Carries SCM, FGM and FC

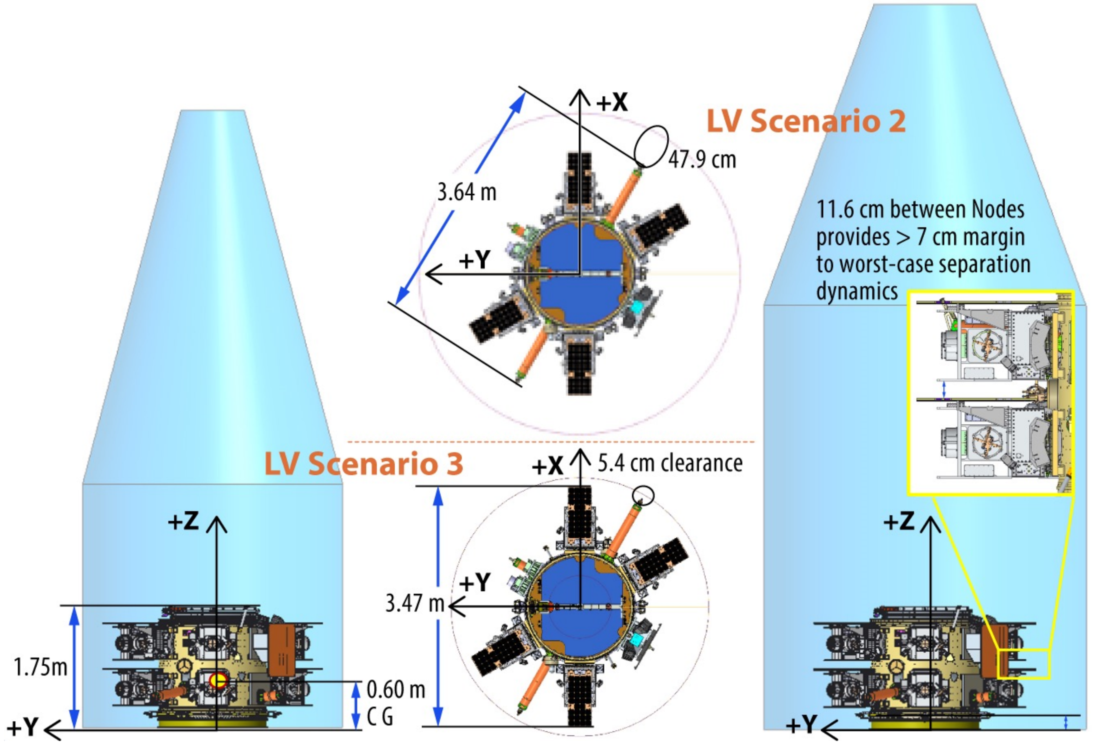


HelioSwarm Observatory:
Provides 1st measurement of energy cascade rate at multiple scales simultaneously



Launch Configuration

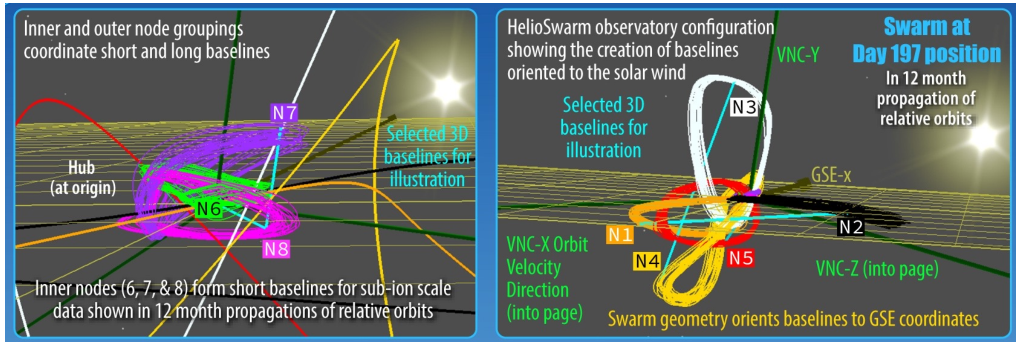


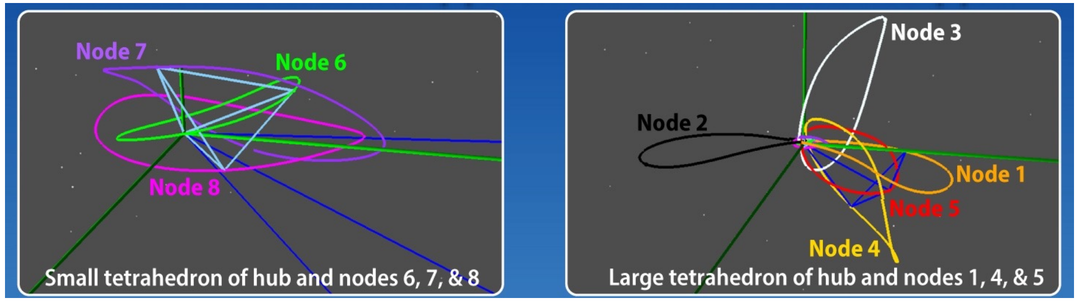


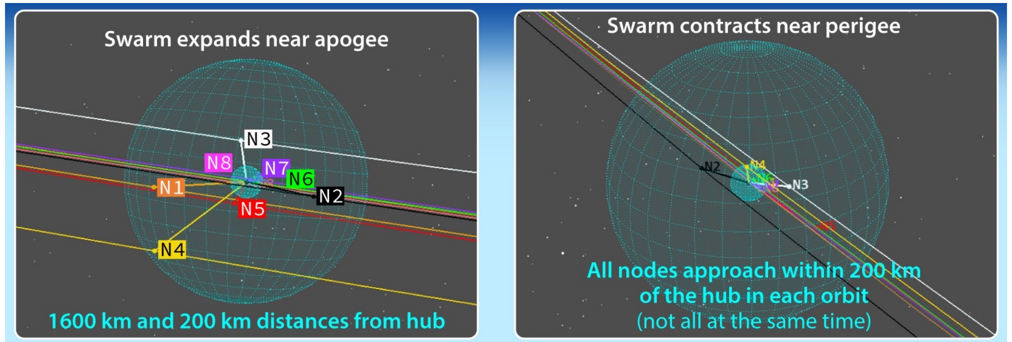
x8

Swarm Orbit Dynamics

- Multi-point/Multi-scale observation geometries
  - Baselines
  - Tetrahedra
- Targeted relative motion of the 9 spacecraft with respect to each other creates geometries
- Bulk motion of all 9 spacecraft is the HEO orbit, with the 8 nodes co-orbiting the Hub
  - HEO orbit period is 14 days
  - Co-orbits are also 14 days
- Swarm naturally expands at apogee and contracts at perigee
- Swarm Orbit Trim Maneuvers (OTMs)
  - 1-2 per Node per Orbit
  - Low-thrust / long-arc

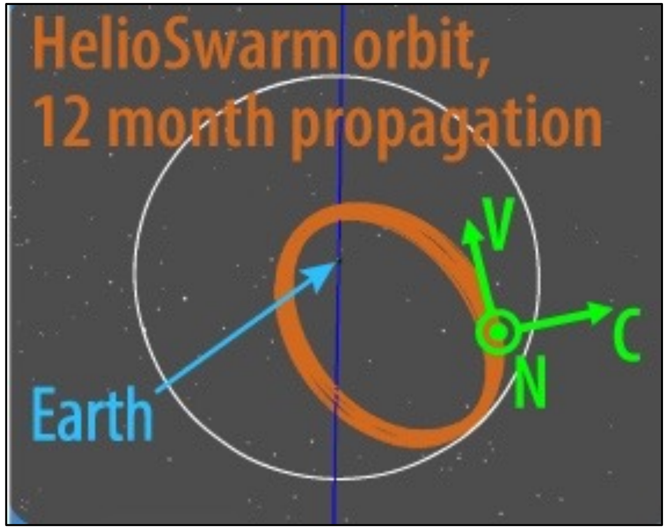




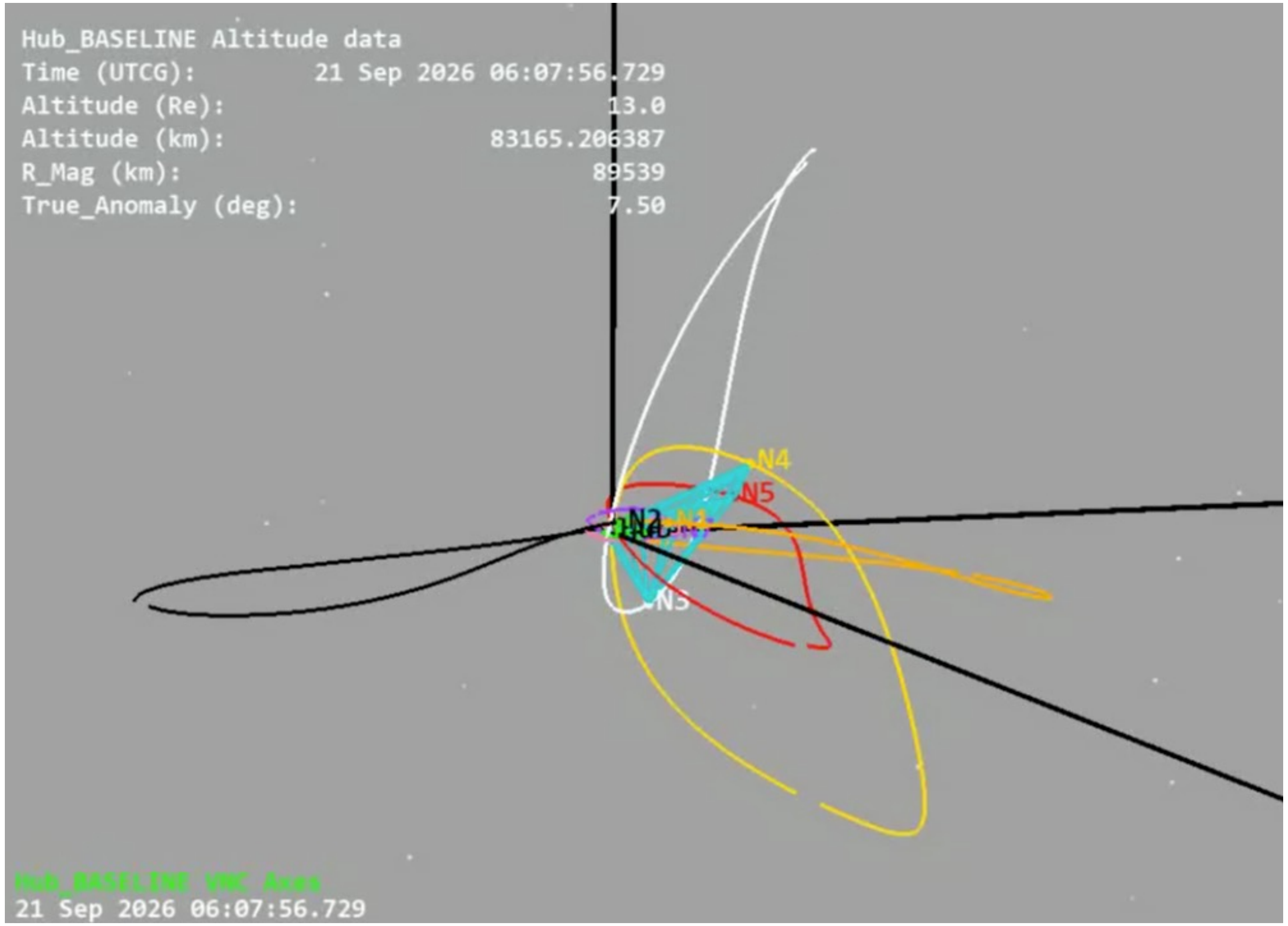


Swarm Orbit Dynamics

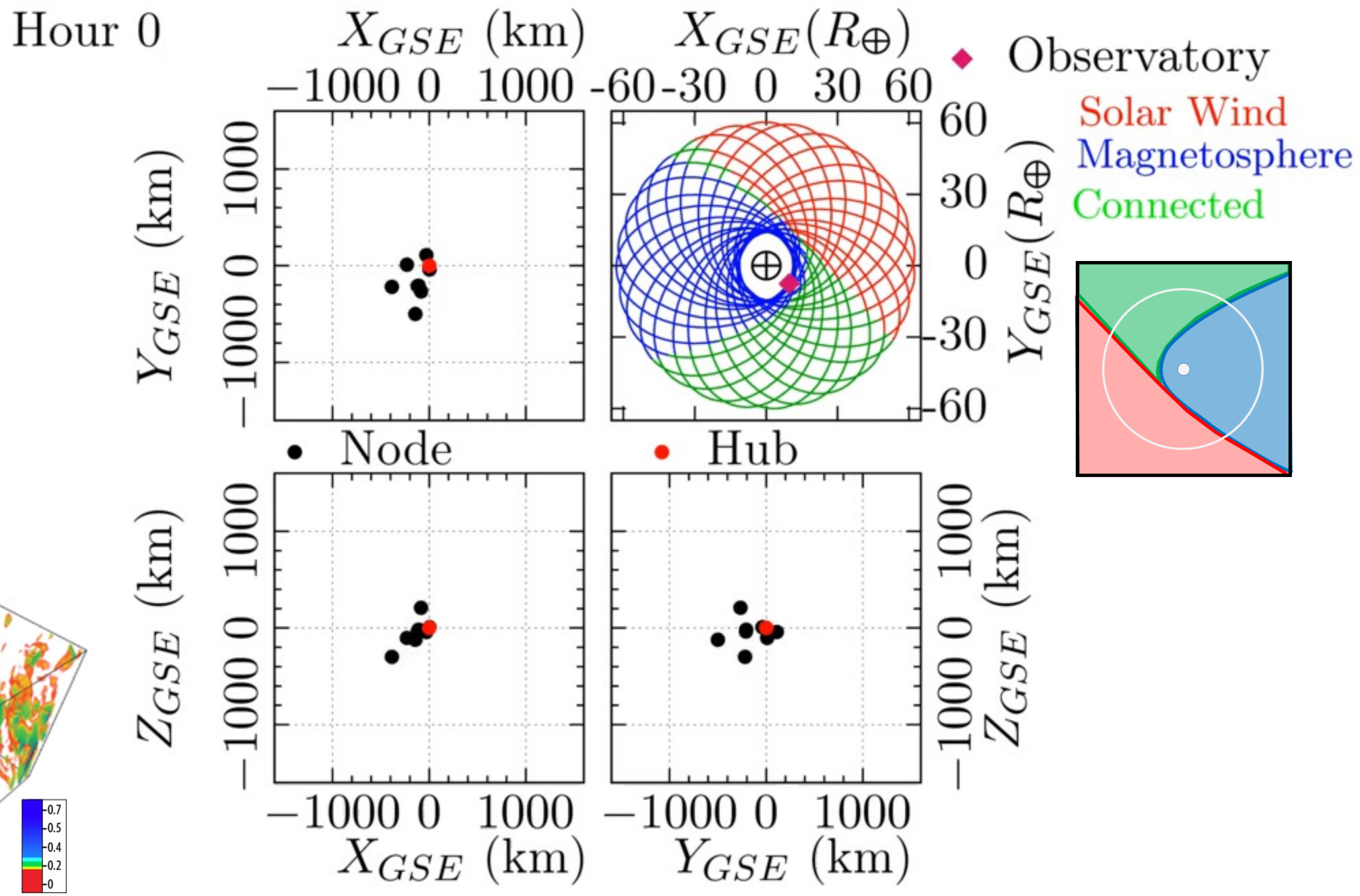
Bulk Motion

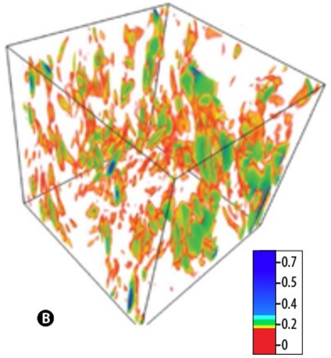


Relative Motion

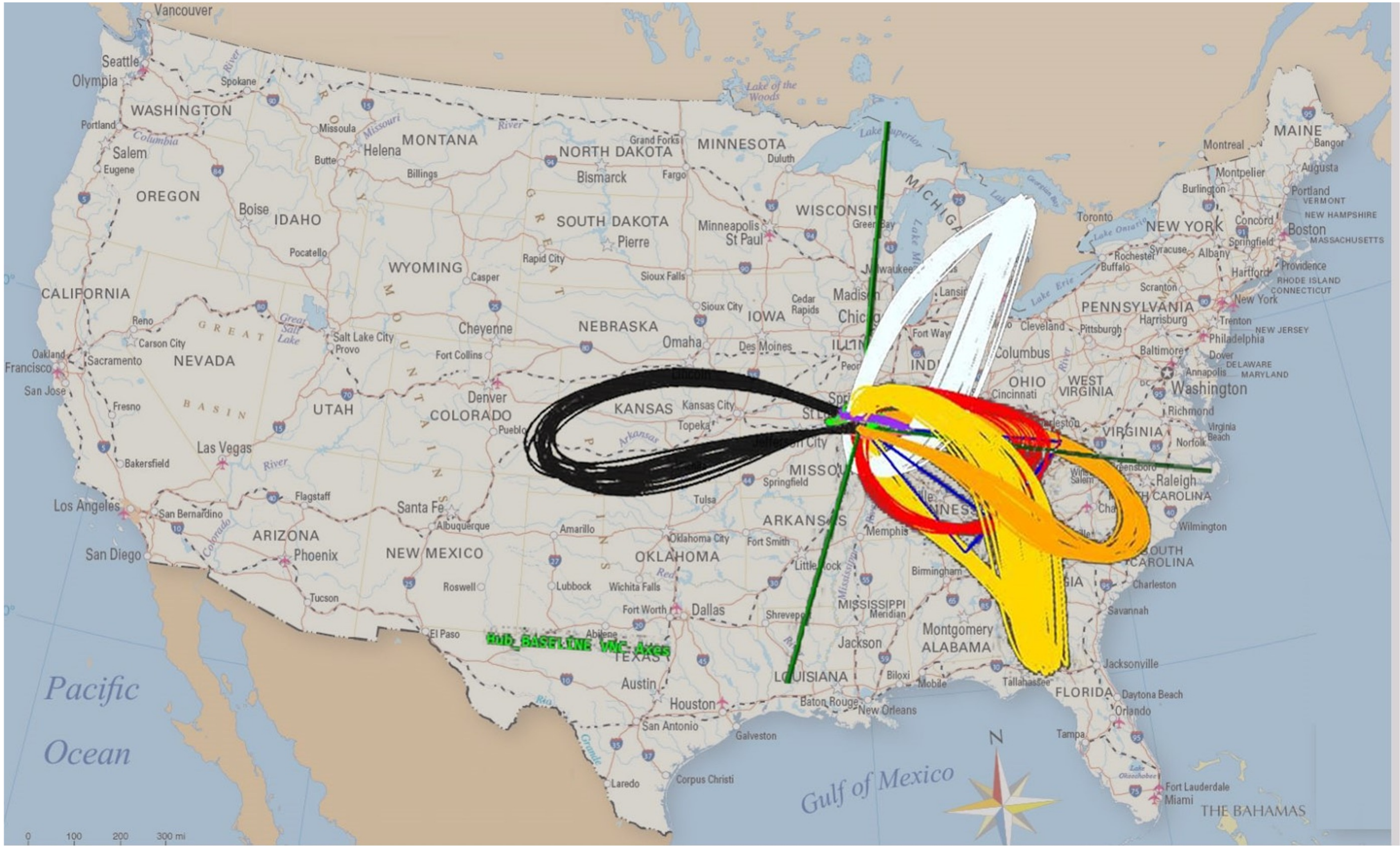


Swarm Orbit Dynamics

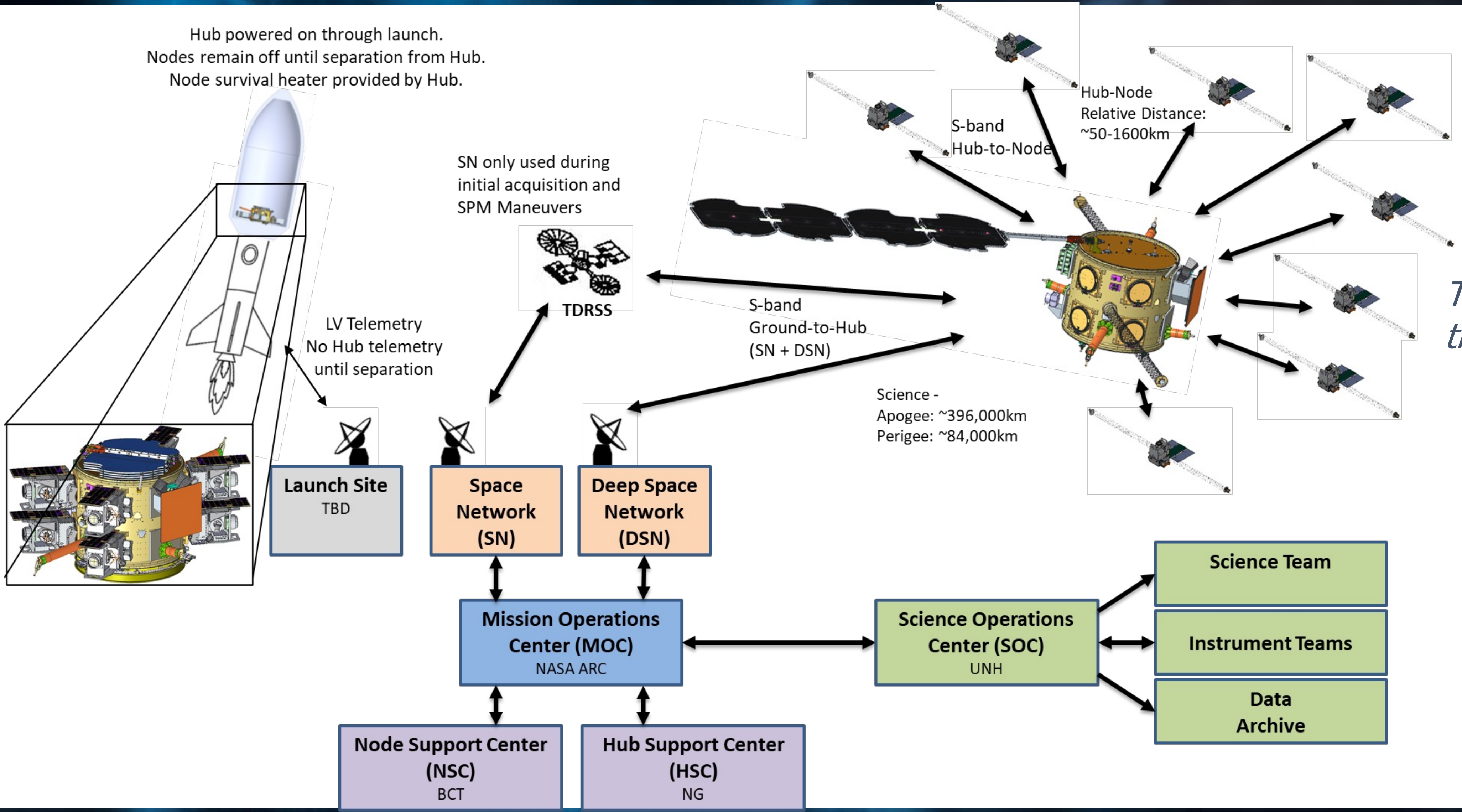




HelioSwarm Observatory in Relative Scale

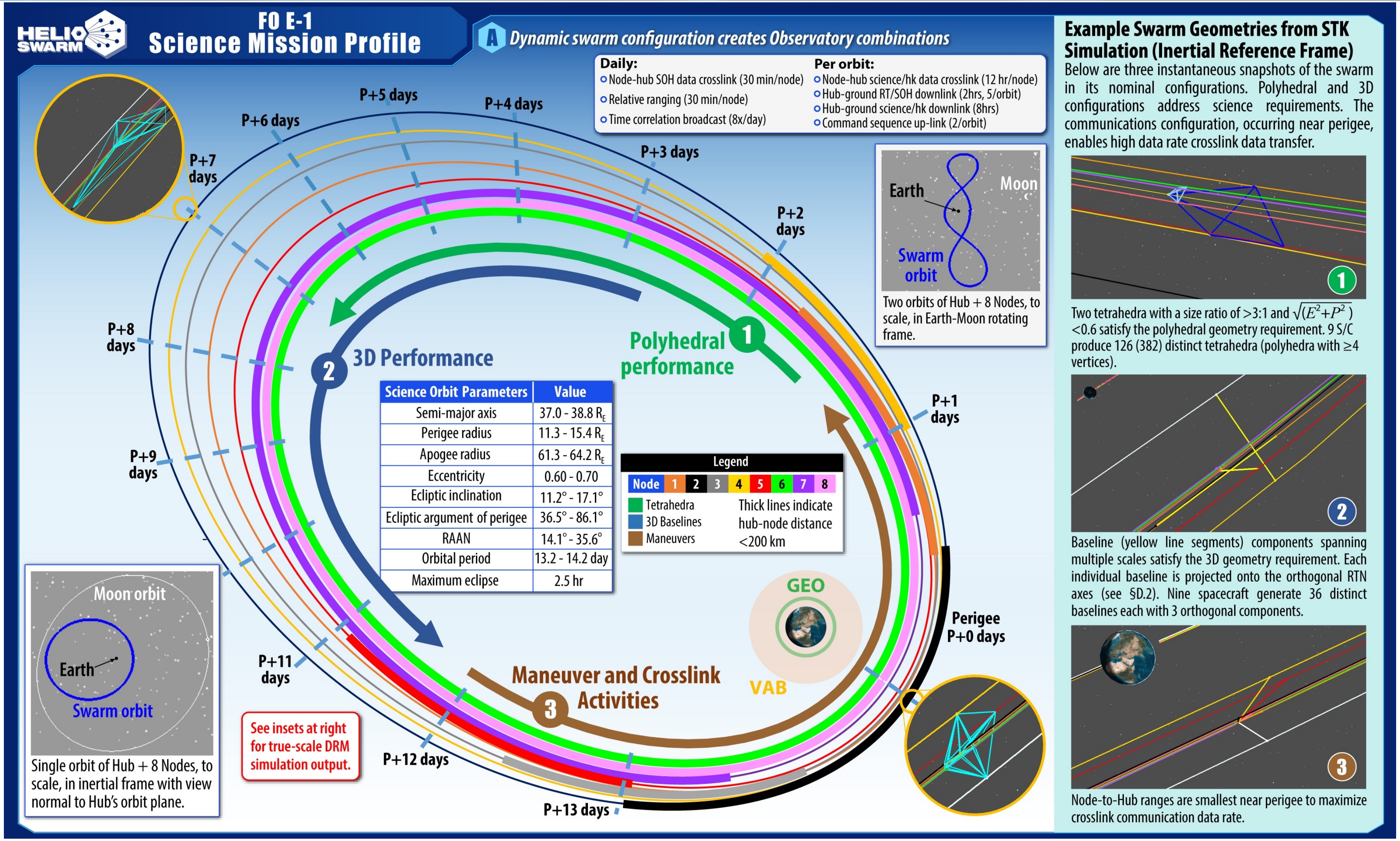


Mission Architecture



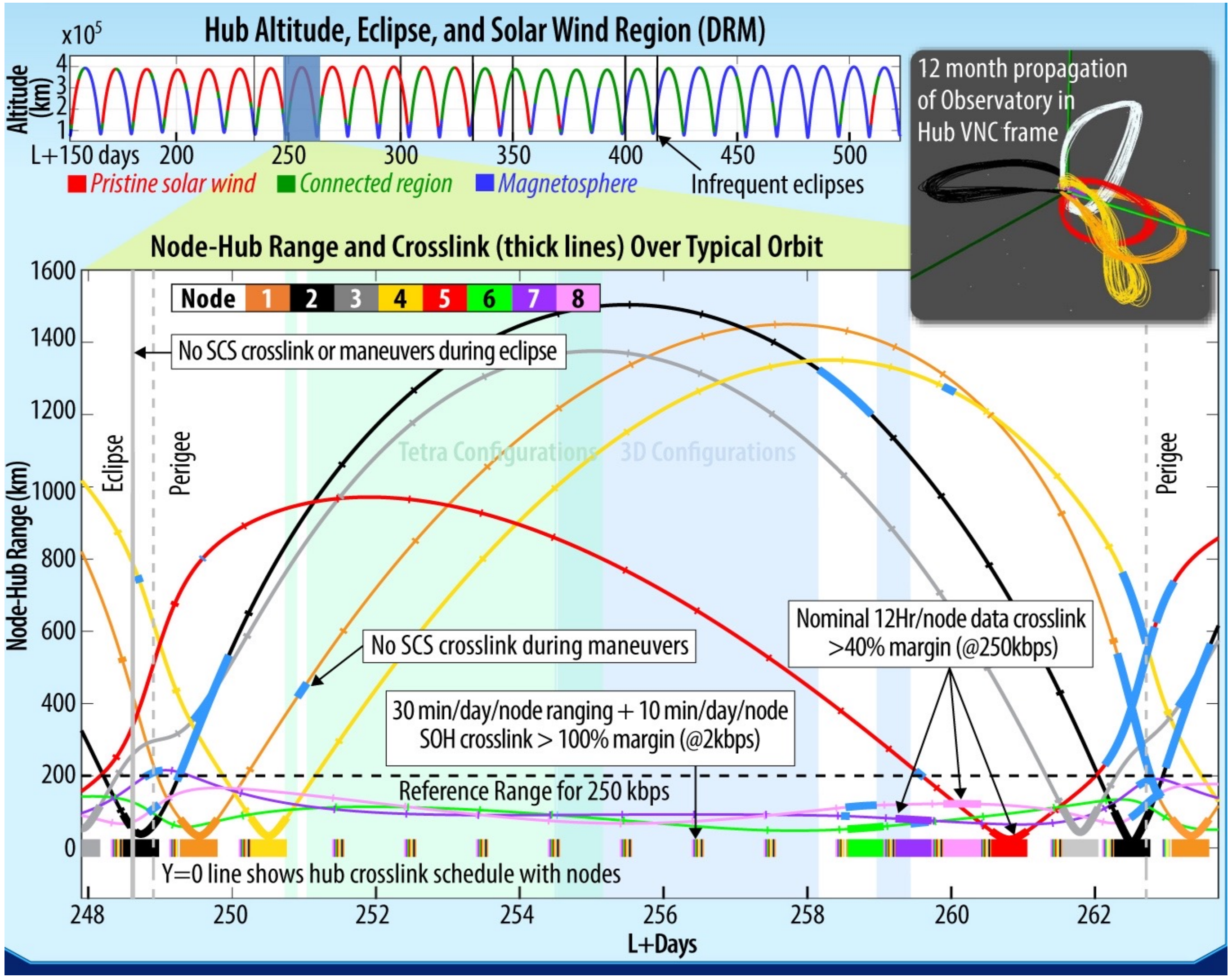
The swarm is the observatory

Science Phase Overview



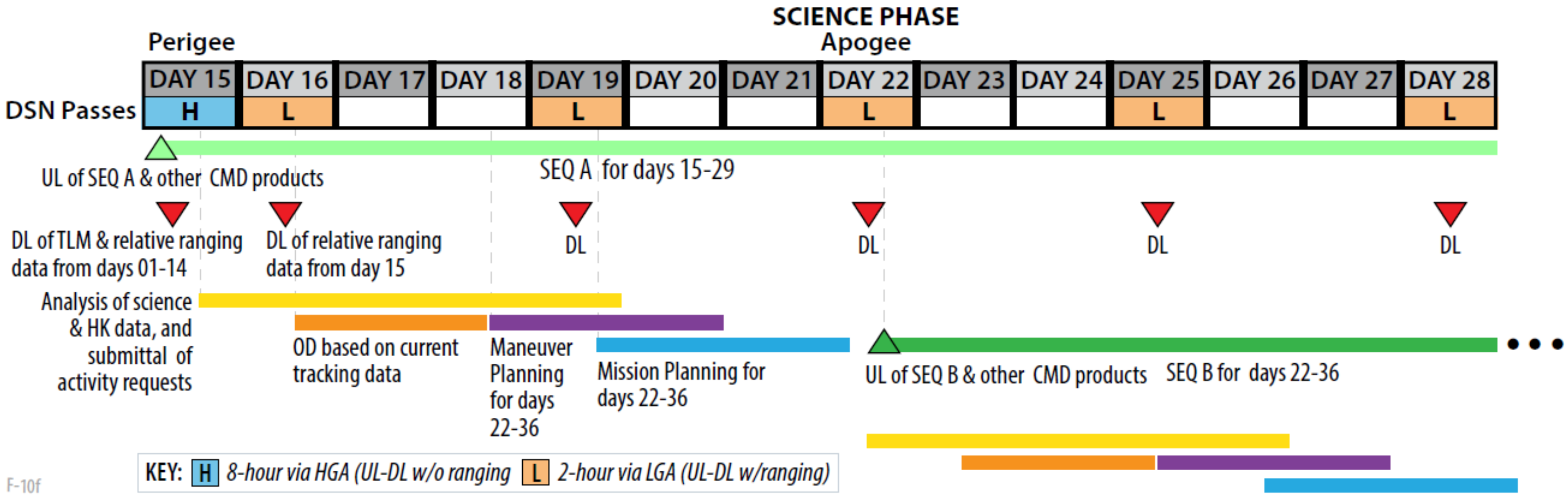
Science Orbit Parameters	Value
Semi-major axis	37.0 - 38.8 R_E
Perigee radius	11.3 - 15.4 R_E
Apogee radius	61.3 - 64.2 R_E
Eccentricity	0.60 - 0.70
Ecliptic inclination	11.2° - 17.1°
Ecliptic argument of perigee	36.5° - 86.1°
RAAN	14.1° - 35.6°
Orbital period	13.2 - 14.2 day
Maximum eclipse	2.5 hr

Science Phase Communications



- High-rate node-to-hub data downlinks occur once per orbit near perigee
  - 12 hr / node
- Individual relative orbits are phased to provide separation between node closest approaches
- Revisit pattern repeats each orbit
- Daily node-to-hub SOH and relative ranging
- Node-to-hub contacts are driven by command sequence on the hub

Science Phase Operations Timeline



- High-rate hub-to-ground (includes downlink of all node data) once per orbit (14 days approx.)
- Low-rate SOH and ranging every 3 days, extra around perigee
- Master sequence duration of 2 weeks, produced every week

Mission Ops / Ground System Approach

Mission Operations at ARC

- Wide range of missions supported (Lunar, interplanetary, LEO, nanosats, ISS payloads)
- Multi-Mission Operations Center provides infrastructure
  - Facility
  - Desktop/server hardware
  - Networks
- Projects choose mission ops software
- No single "operations organization" that provides operations staff
  - Researchers and developers allowed to transition back and forth
  - Ops informs research/development, research/development infused back into ops, etc.

HelioSwarm Mission Operations / Ground System Approach

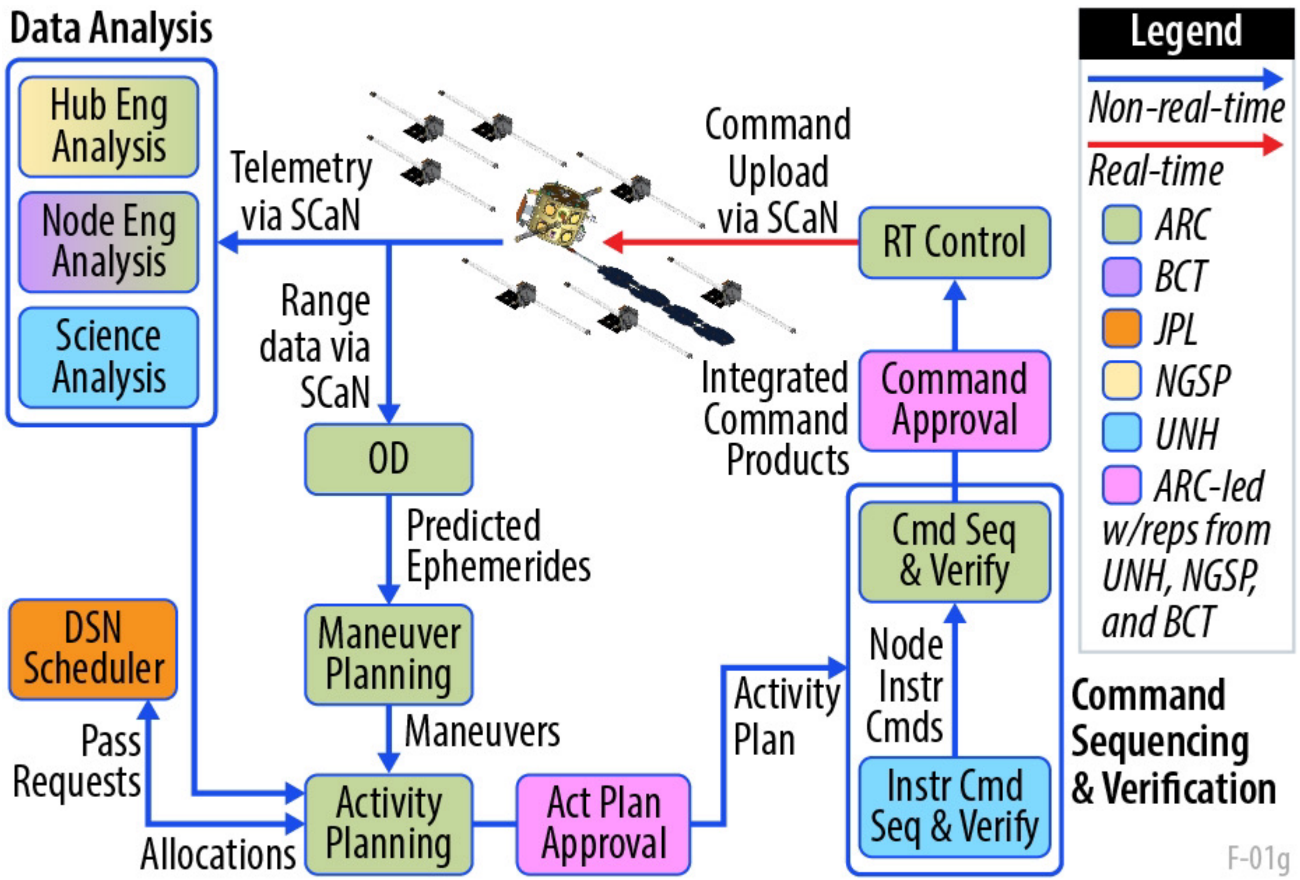
- Swarm of 8 S/C does not necessitate a new wholesale approaches or tools
- Choose heritage tools and processes
  - Preference to those with multi-spacecraft capability
  - Focus on integration and test, develop only when necessary
- Scaling when necessary to meet mission ops cycle efficiency requirements. Approaches:
  - Automation
  - Parallelization
- Design to a specific target team size (proxy for cost)
- Early Agile process to inform requirements for software components with higher uncertainty
- Key MOS positions staffed throughout project lifecycle to keep mission complexity to a minimum

Simplifying Factors for Operations

- **Operate as a Swarm:** All spacecraft supporting the same objective. 9 spacecraft, but only 2 spacecraft types -- the nodes all carry the same flight software and hardware. Single tool-chain for all nodes. Same procedures for all nodes, just run multiple times (either in parallel or serially). **Simple Instrument Operations:** simple streaming modes, no complex pointing or tasking, no rapid observation-to-tasking turn-around needed, no "targets of opportunity"
- **No Hub maneuvers in Science Phase:** the complex portion of the Hub's operations are all completed by the time mission moves into the Science Phase.
- **Simple S/C attitude operations:** Science instruments do not require attitude slews or tasking. The simple sun-pointing is wholly handled by the respective FSWs.
- **Minimal number of real-time contacts:** 5 contacts per orbit, and only with the Hub.
- **No CARA coordination** needed during the Science Phase (internal checks on close approaches will be performed, but coordination with other orbiting assets, which is time consuming, not required).
- **Numerous others**

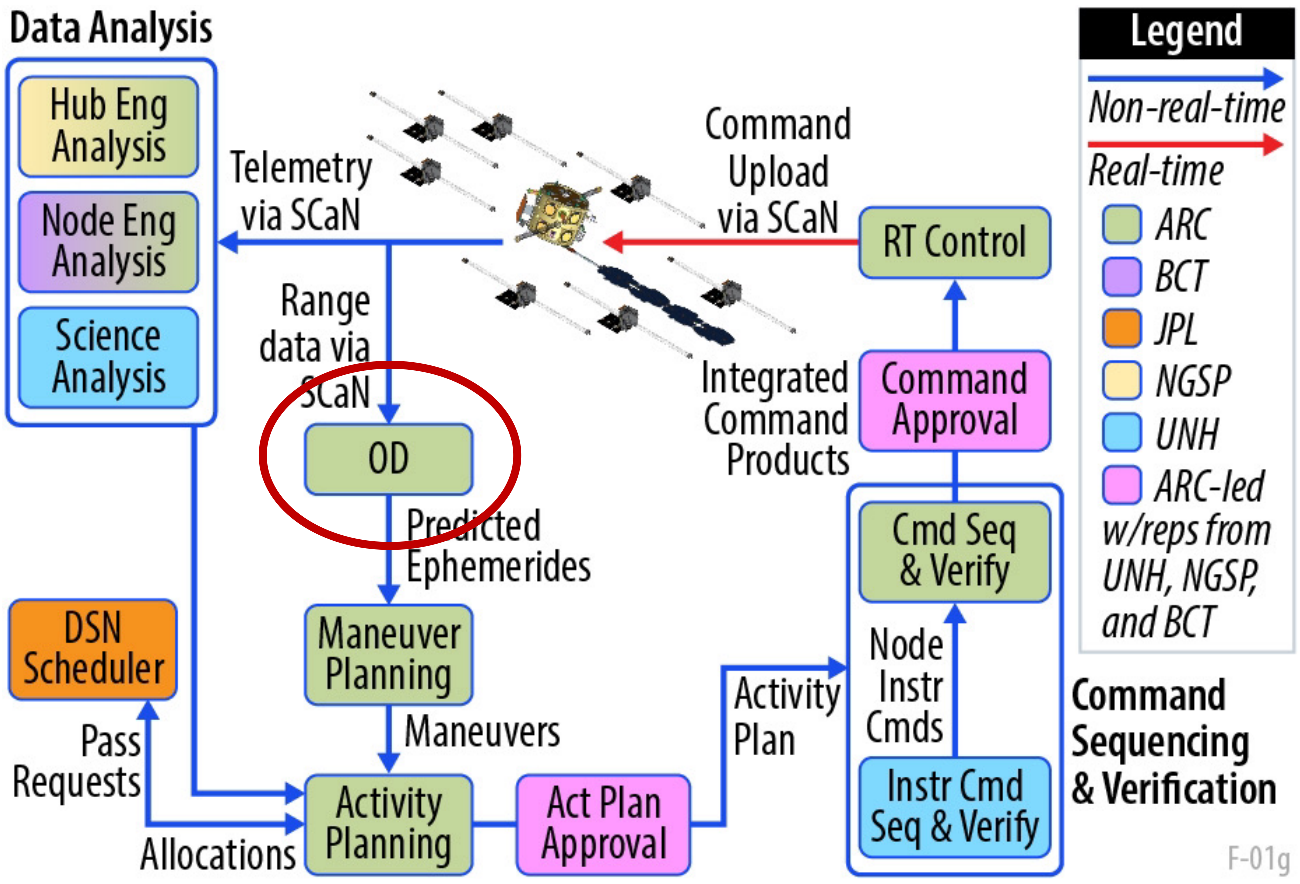
Lower complexity spacecraft and instruments lowers required MOS process complexity

Mission Operations Cycle



- One complete cycle per 7-day week
- Shorter SOH monitoring cycle every three days
- Scaling Approaches:
  - Automation (A)
  - Parallelization (P)
  - Simplify (S)

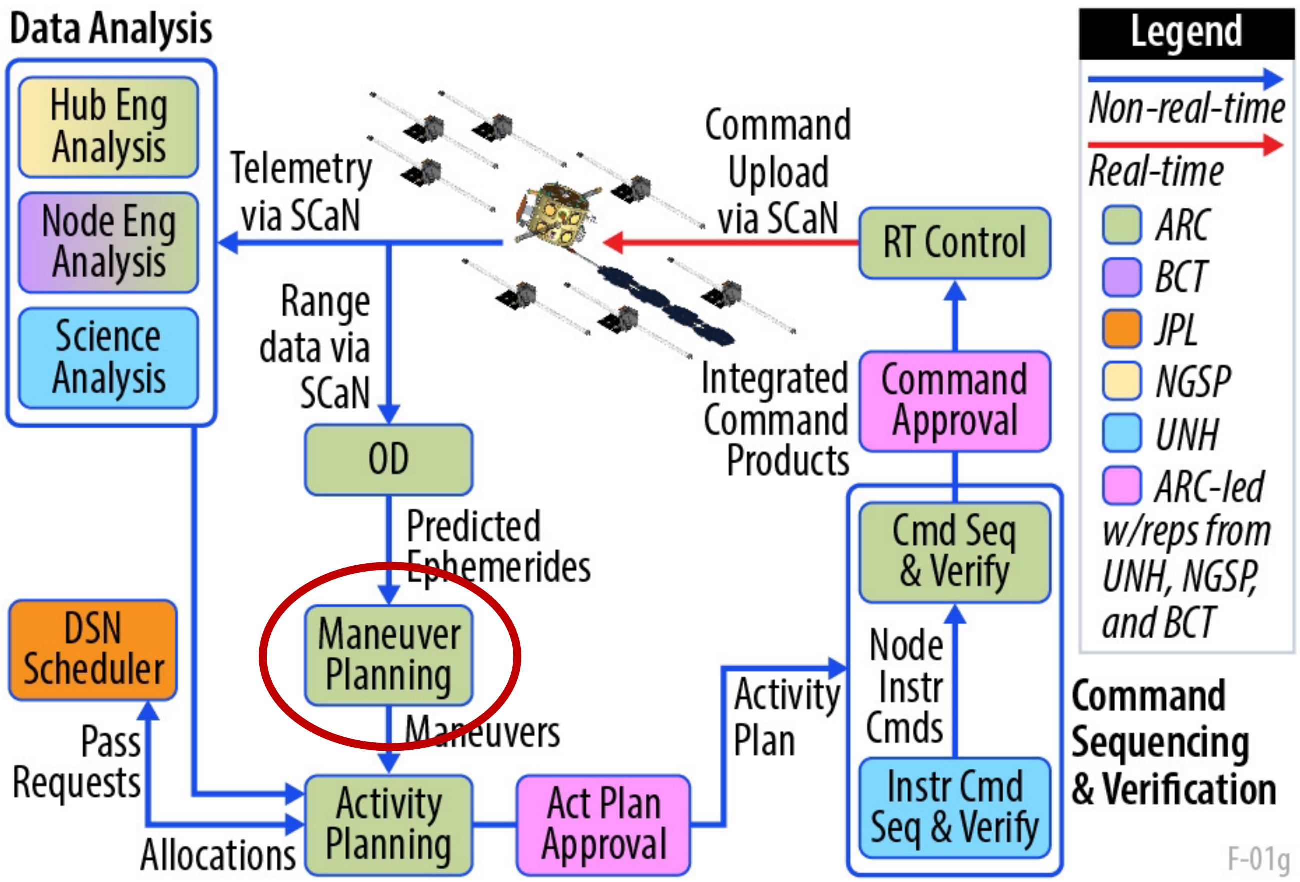
Mission Ops Process Approach



Orbit Determination:

- (P) Process hub and node tracking and node relative ranging data in single ODTK filter.
- (A) Use heritage FDS platform (ref LADEE, STPSat-5, CYGNSS and Starling) and procedures, including scheduled job functionality (time-based or file delivery-based triggers).

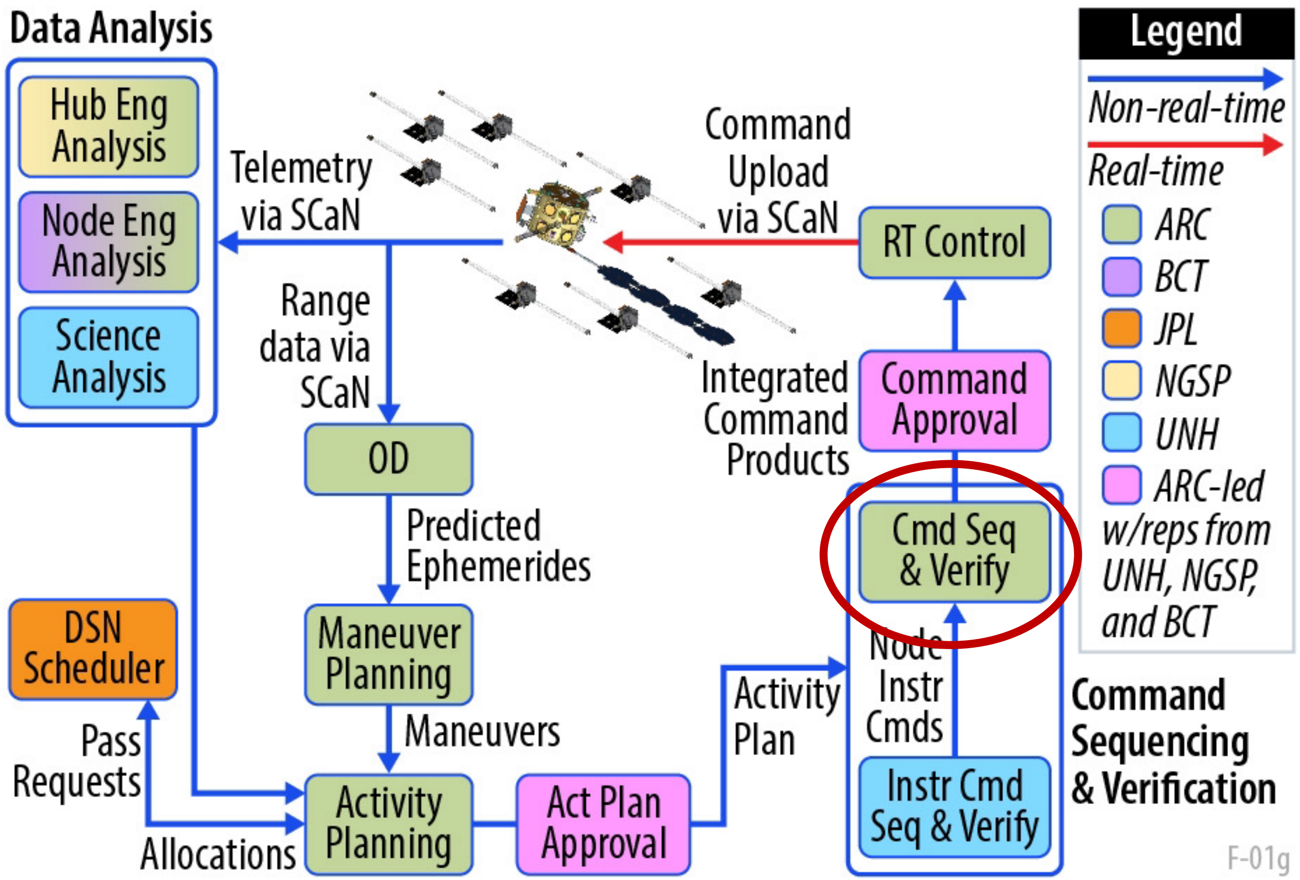
Mission Ops Process Approach



Maneuver Planning

- (A) Use heritage FDS platform and procedures:
  - L3 Flight Dynamics System based on AGI/Ansys STK and ODTK
  - Used at ARC for LADEE, STPSat-5, and Starling (multi-spacecraft)
- (P) 1-3 OTMs planned within single procedure run
  - Max number of planning runs per cycle is 8 (on per node)

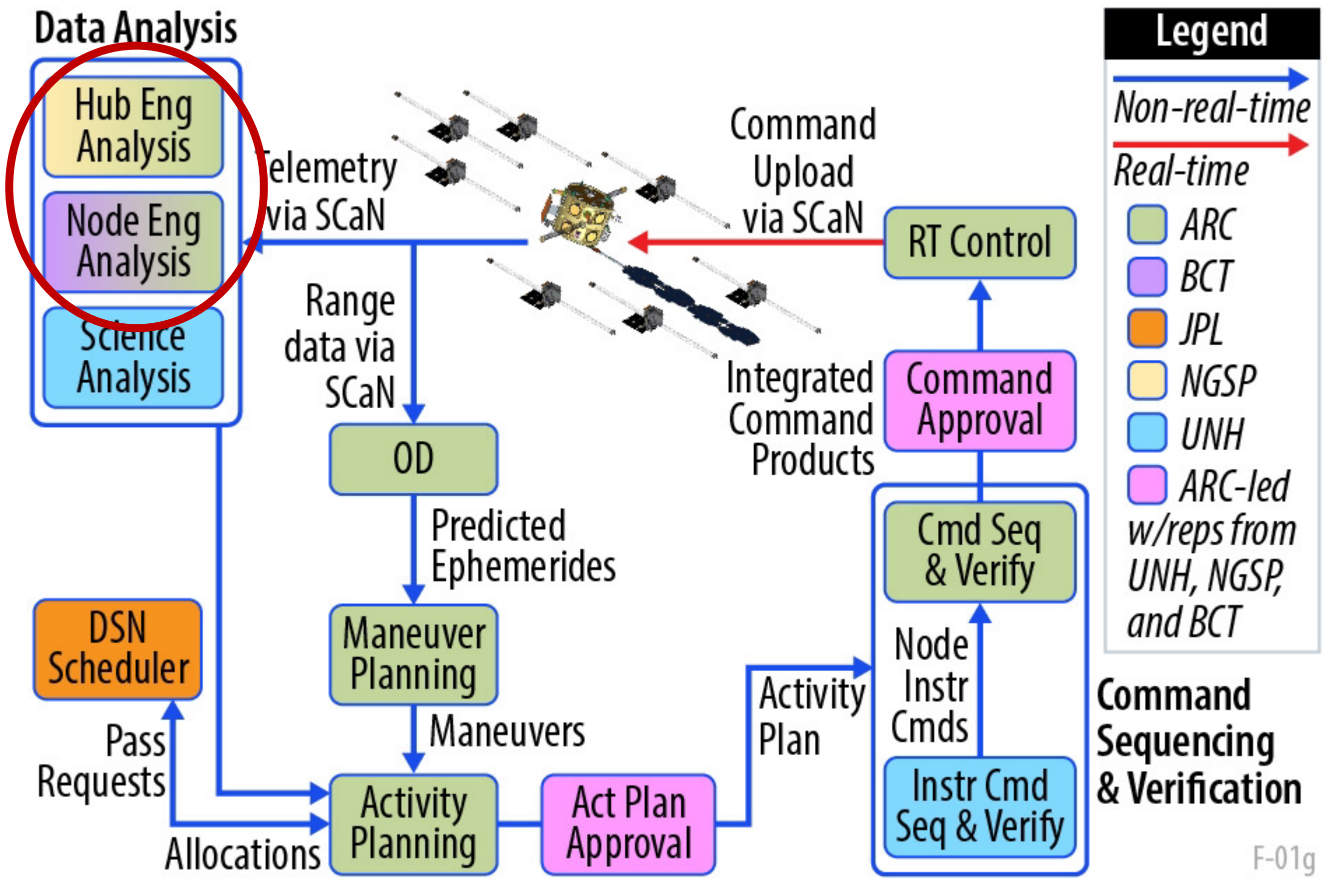
Mission Ops Process Approach



Command Sequencing / Sequence Verification

- (S) Tasks in Science Phase are repetitive, and nearly identical between nodes, allowing for the extensive use of sequence templates
- (A) Application of sequence templates
- (S) Simple node attitude profile doesn’t require high- fidelity attitude simulation; rely on static flight rule checking code
- Open Questions / Trades:
  - Identification of routine activities that would drive need for routine hardware simulation of multiple S/C; **difficult to parallelize**
  - Framework for application of sequence templates vs. reuse of older tools

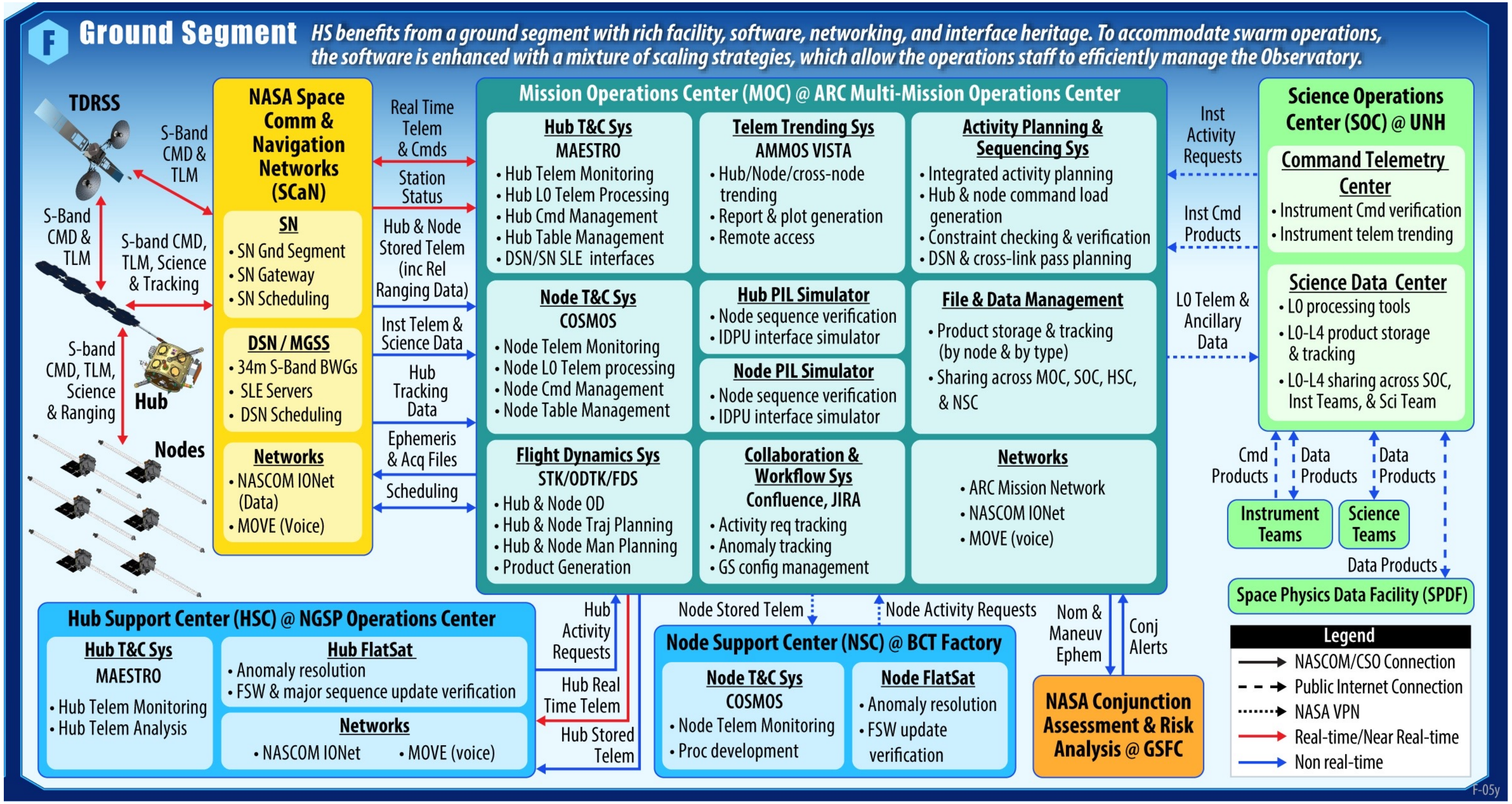
Mission Ops Process Approach



Engineering Analysis

- (A) Use OpenMCT/VISTA to view trending data from all S/C in one environment
- (A) Standard L0 processing and limit checking in T&C System:
  - MAESTRO for Hub
  - COSMOS for Nodes
- Open Trade:
  - Run single instance of COSMOS configured for all S/C
  - Run multiple instances of COSMOS in virtualized and/or cloud environment for parallel processing

Preliminary Ground Segment Architecture



Conclusions

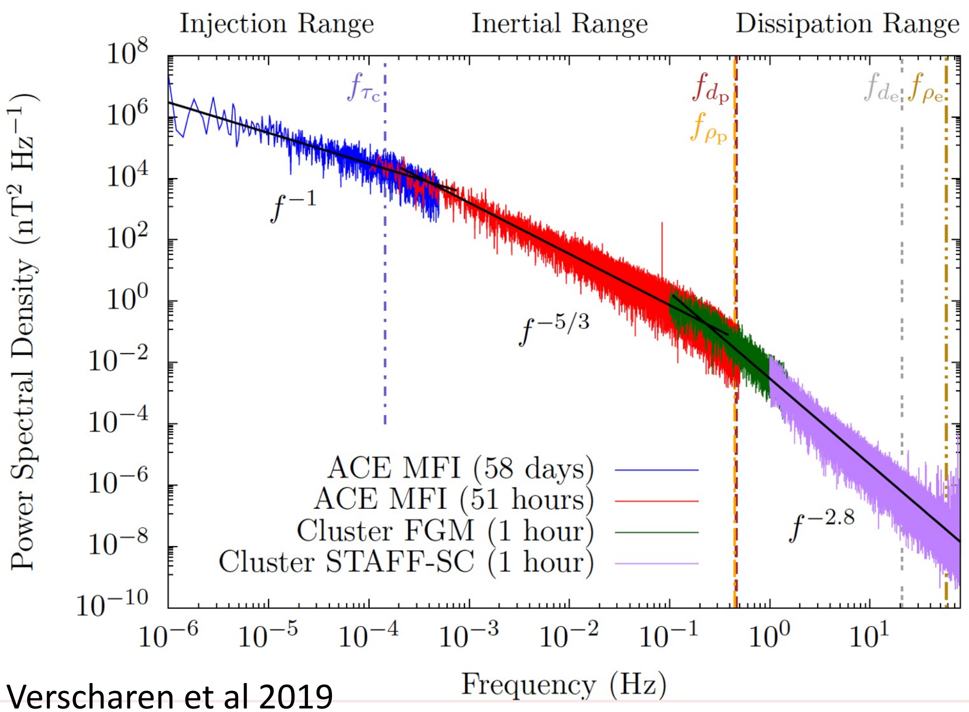
- Exciting and novel mission with potential for foundational science
- Project-wide goal of minimizing complexity; operations perspective throughout life-cycle
- Significant but not insurmountable ops / ground system challenges
- Updates at future SpaceOps events

Questions & Discussion

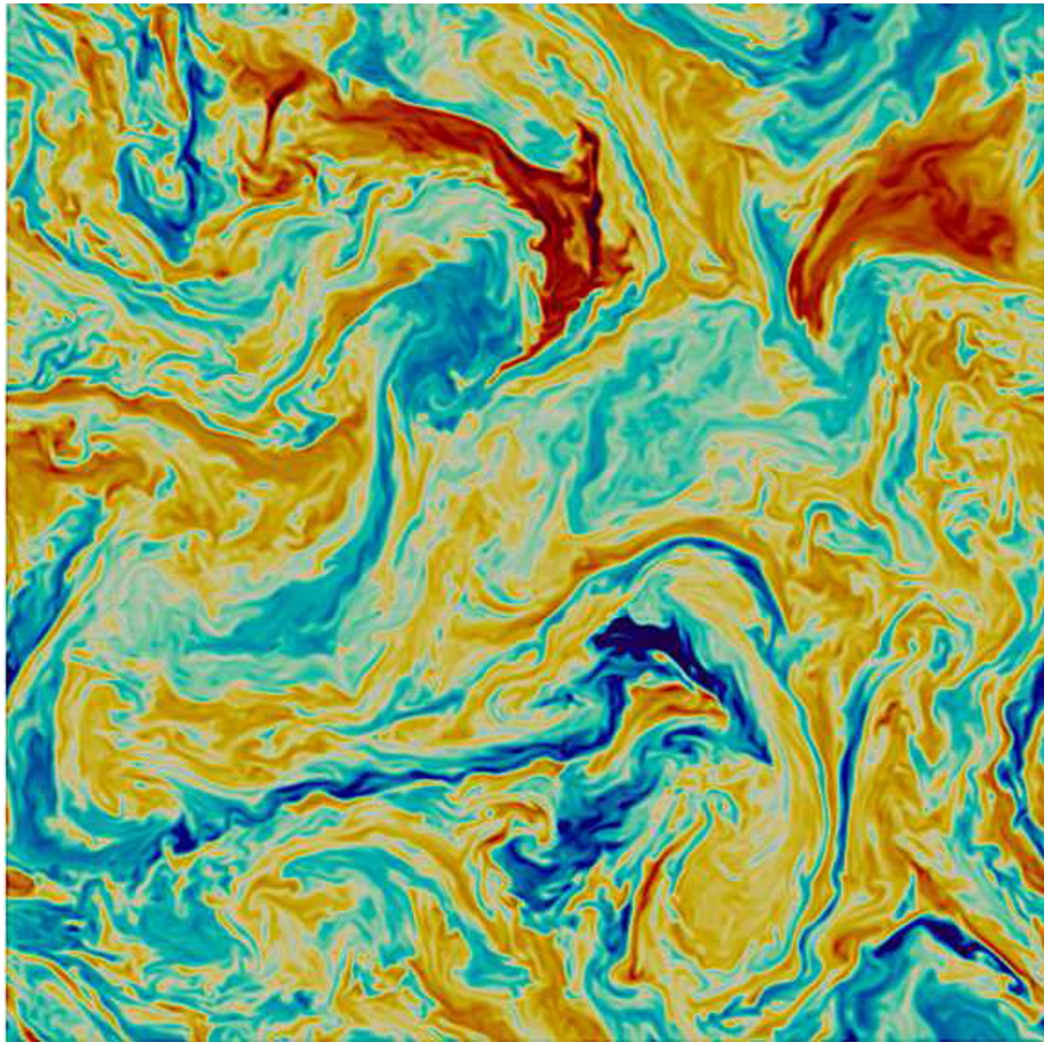
Back-up

A More Detailed Picture of Space Plasma Turbulence

- Nonlinear couplings produce ranges with power-law scalings
- Intermittent Structures are also naturally formed and are associated with enhanced dissipation



Verscharen et al 2019

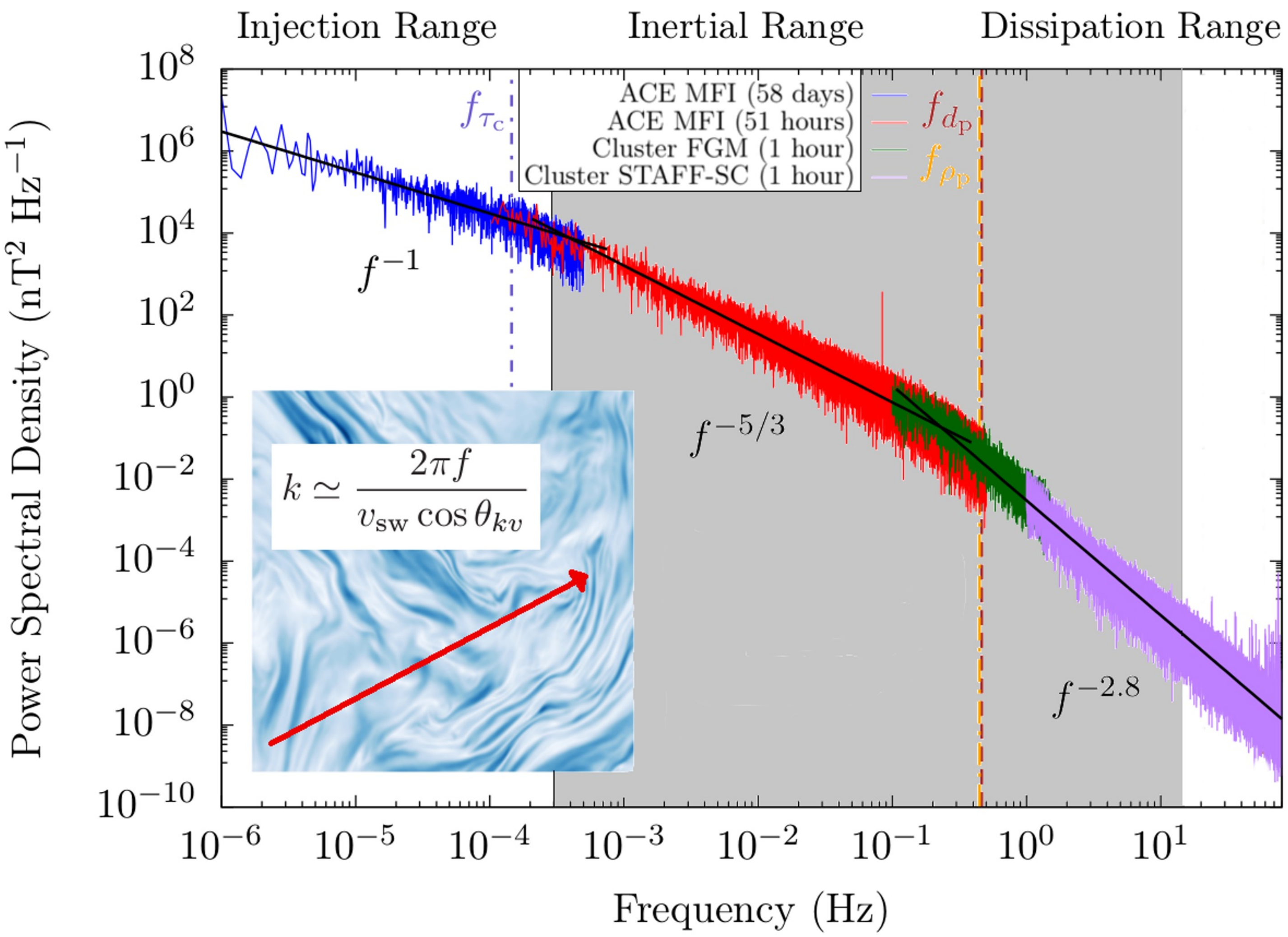


Meyrand et al 2019

Limitations of a Single Spacecraft

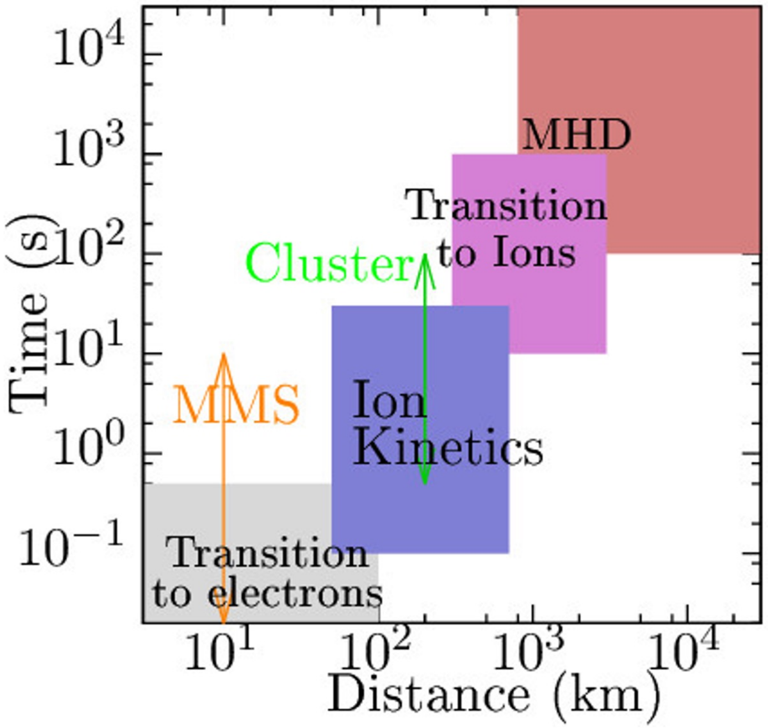
- Past single-spacecraft missions relied on limiting assumptions to disentangle spatial features and temporal dynamics, a mapping between temporal measurements and spatial structure is known as **Taylor's Hypothesis**

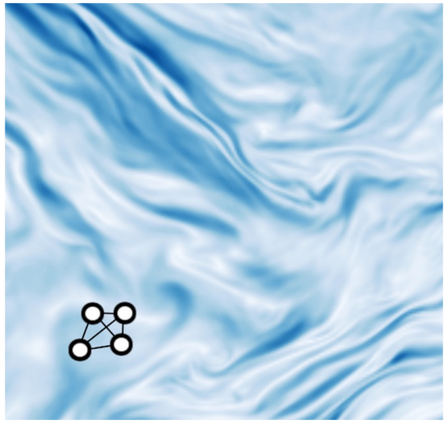
- The majority of our observations of heliospheric plasmas is limited to a single point (e.g. ACE, Wind), often requiring the combination of many different types of turbulence in order to have a statistically large enough data set.



Multipoint, Single Scale Studies - isn't this already solved?

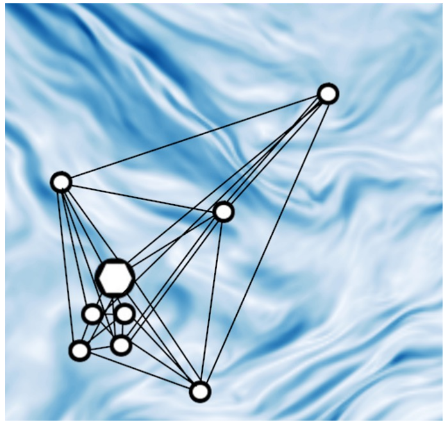
- Previous Multi-spacecraft missions (e.g. Cluster and MMS) revolutionized our understanding of the spatial structure of some plasma processes by measuring quantities over finite volumes rather than at a point.
- MMS optimized for probing single scales from ~5 to ~100 km; excellent for electron microphysics of reconnection and final endpoint heating of electrons by turbulent cascade.
- However, 4-spacecraft missions probe only a <u>single scale size at a time</u>.
- Turbulence demands <u>simultaneous multiscale</u> measurements

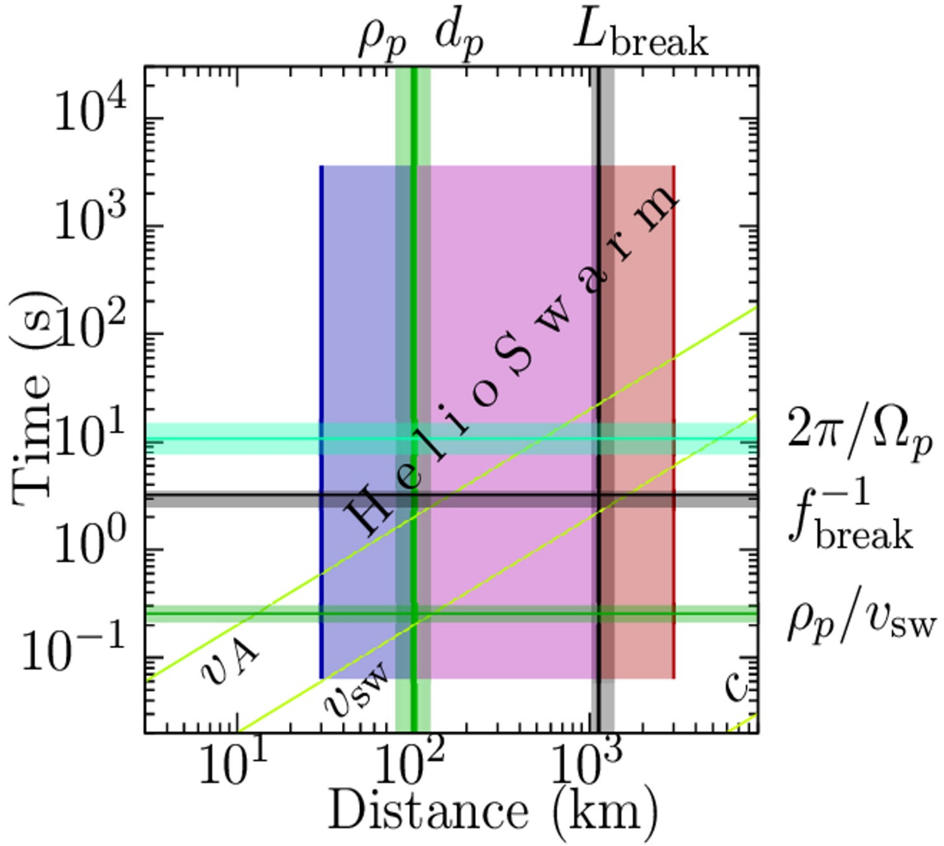




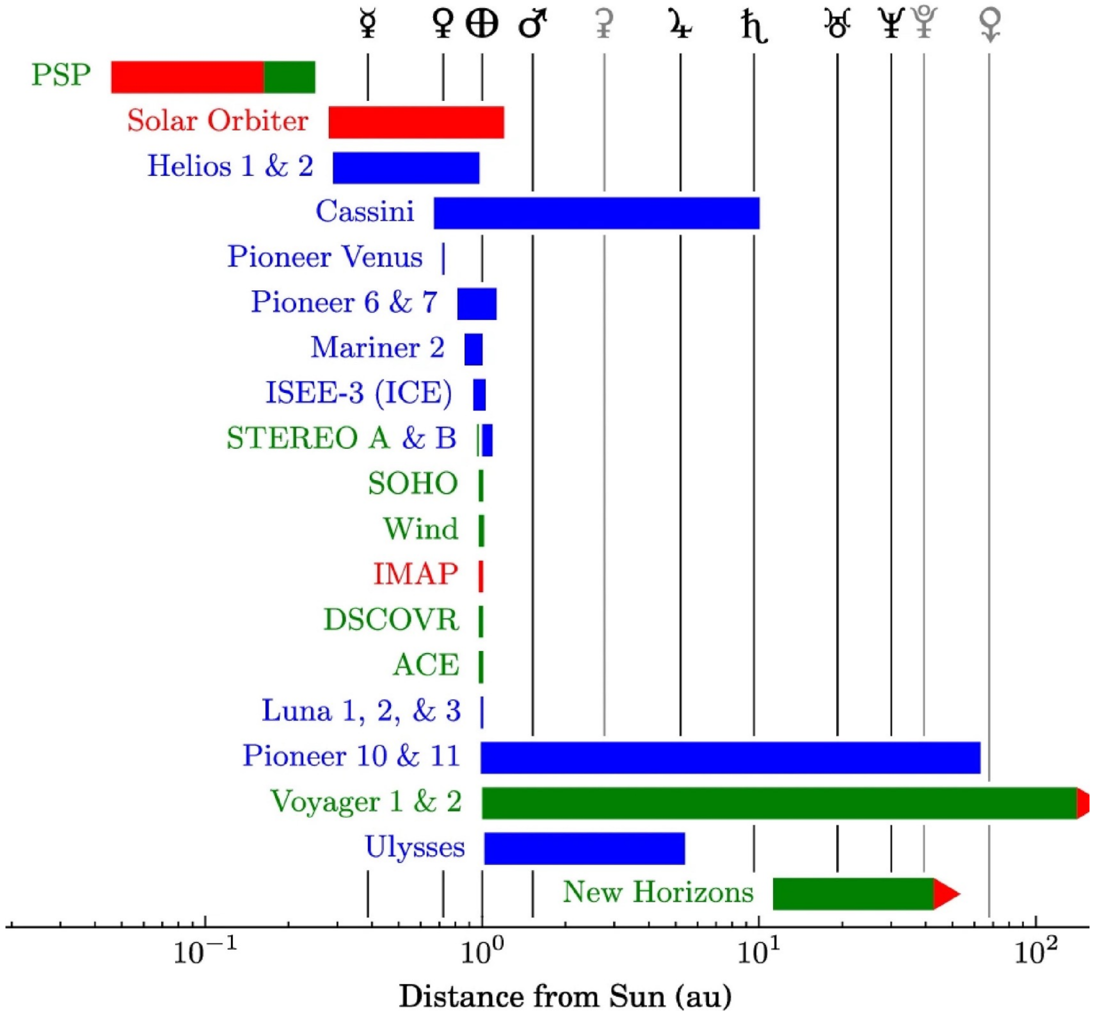
Swarm of S/C Yield Simultaneous, Multiscale 3D Measurements

- In order to transform our understanding of the underlying physical processes, we need to simultaneously measure the solar wind plasma at many points, with separations between the spacecraft spanning MHD and ion scales, as well as the transition region in between.
- These measurements must be made sufficiently rapidly to capture ion scale structures advecting over the observatory, while simultaneously hours long, low-frequency processes.





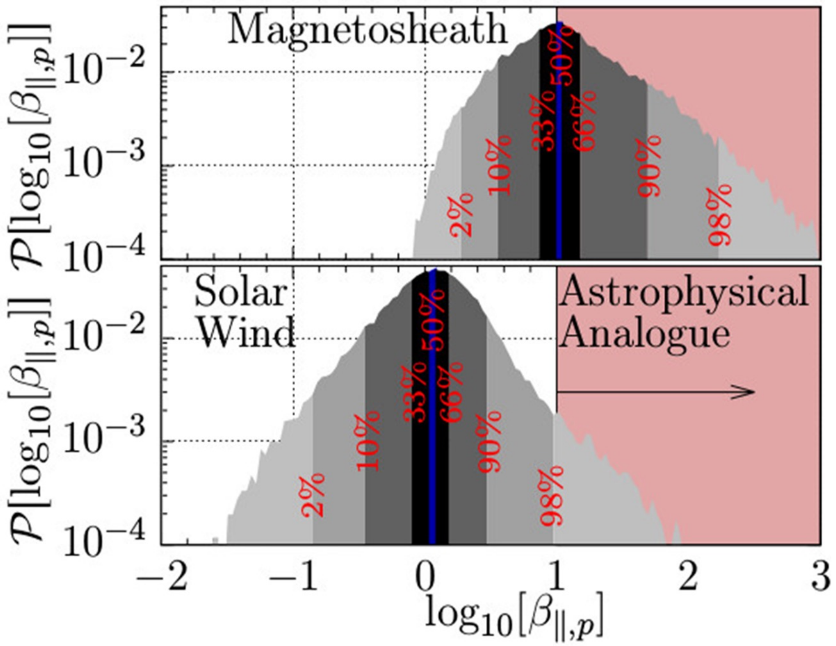
The Solar Wind as a Natural Laboratory for Studying Plasmas



Verscharen et al 2019 LRSP

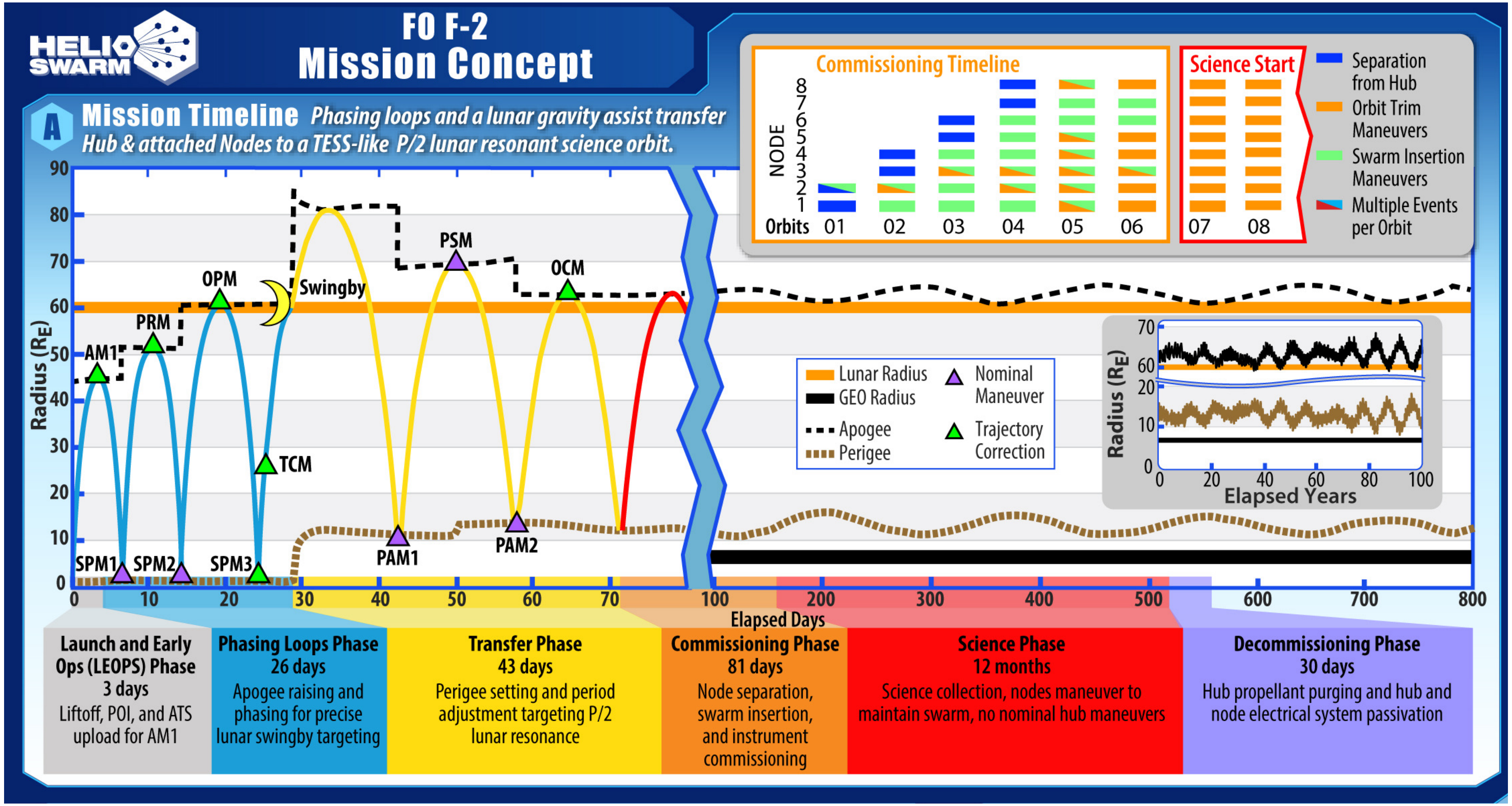
-The Sun's atmosphere expands into a hot (~10 eV) diffuse (~5/cc) magnetized (~6 nT) weakly collisional plasma by the time it reaches Earth.

-There is significant variability in characteristic scales and dimensionless parameters, enabling local measurements to be used to study a variety of different processes.



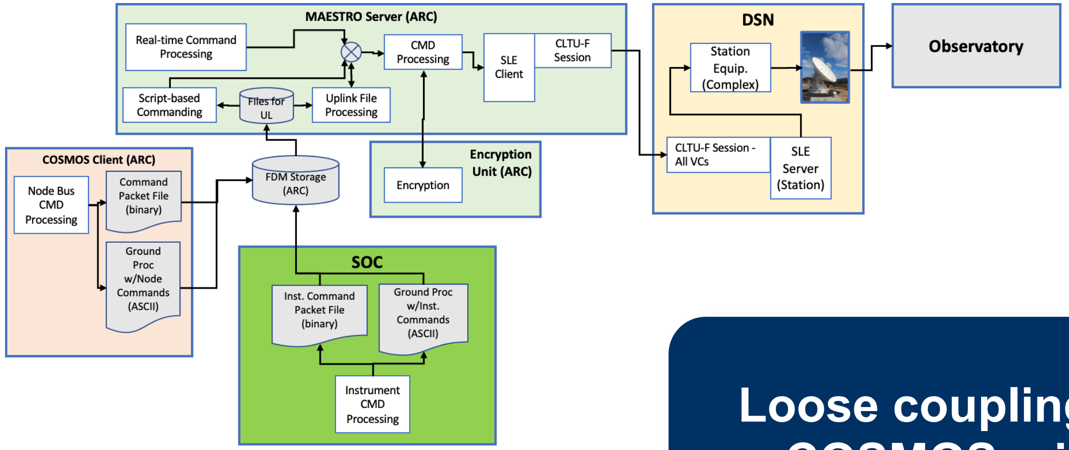
For statistical studies of plasma conditions at 1 au, see Klein & Vech RNAAS 2019, Wilson et al ApJS 2018, and "**A Quarter Century of Wind Spacecraft Discoveries**" by Wilson et al 2021.

Mission Timeline



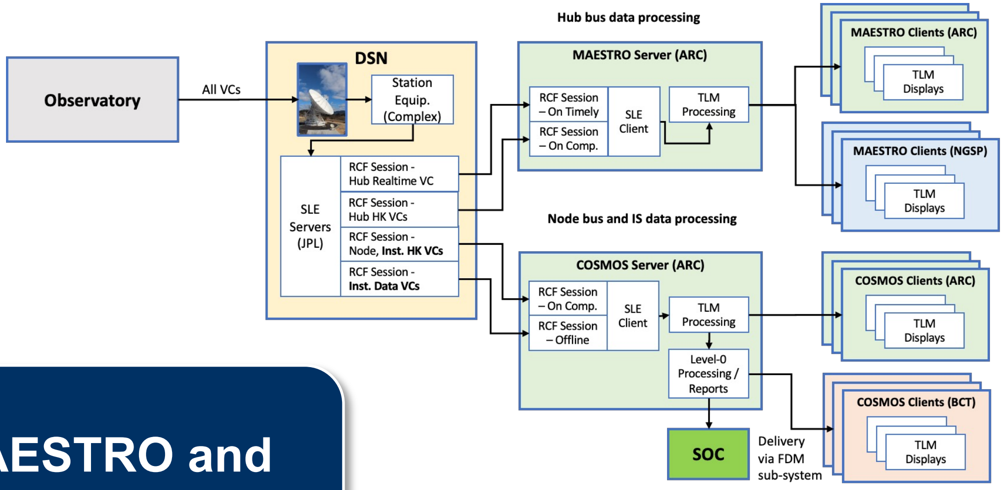
Dual T&C System Approach

- Downlink data flow completely decoupled via the use of CCSDS virtual channels and leveraging DSN functionality
- Uplink data flow provided by file exchange only, utilizing existing MAESTRO and COSMOS functionalities



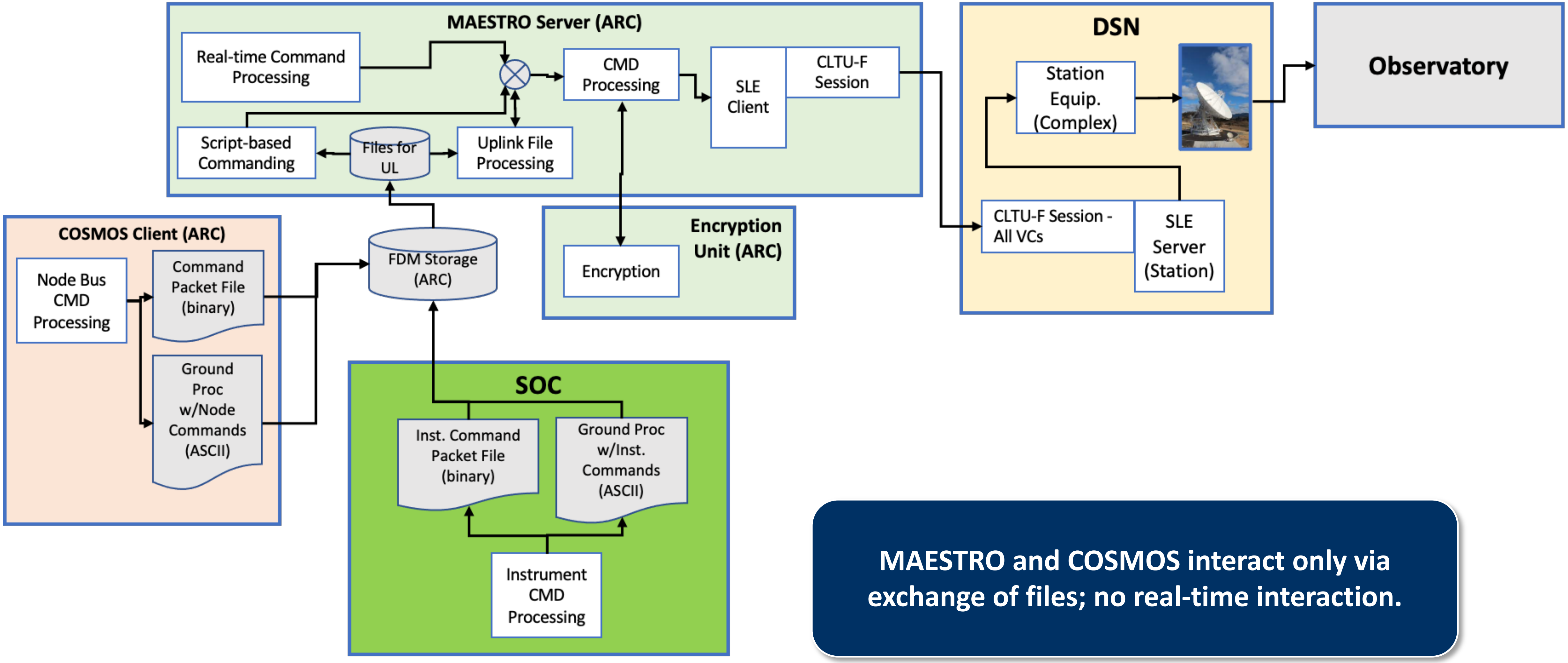
Commanding Data Flow

Loose coupling between MAESTRO and COSMOS minimizes integration risk



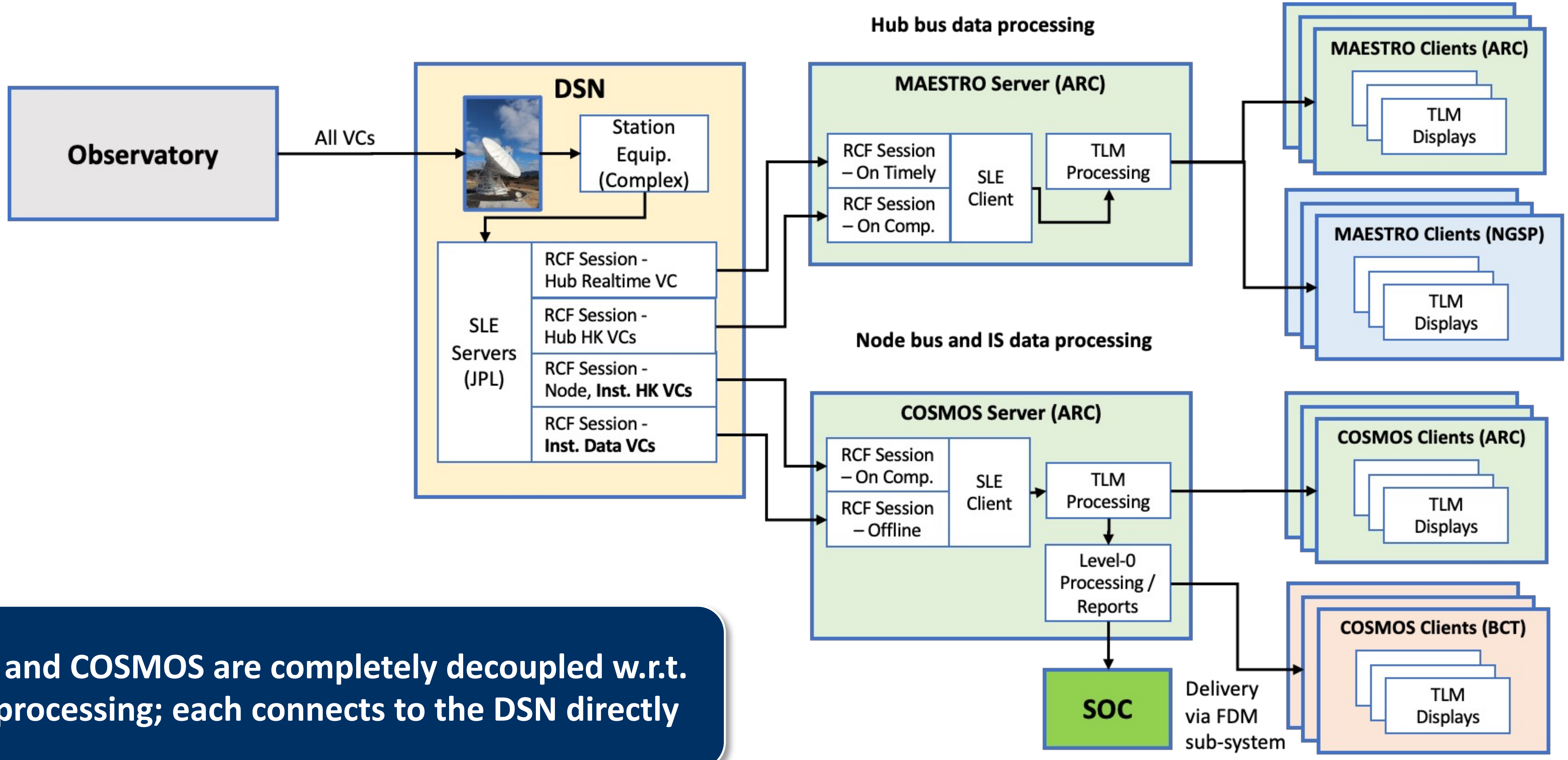
Telemetry Data Flow

SQRL C23 Part B
Uplink Data Flow Concept



MAESTRO and COSMOS interact only via exchange of files; no real-time interaction.

SQRL C23 Part B
Downlink Data Flow Concept



MAESTRO and COSMOS are completely decoupled w.r.t. downlink processing; each connects to the DSN directly

HelioSwarm Mission Operations / Ground System Approach

- Phase A:
  - Use previous experience to derive staff size and shift profile (proxy for cost)
  - Mission complexity comparisons to justify estimates
  - Preliminary ground architecture and software component selections
- Phase B Prep. / Phase B:
  - Use staff size and shift profile as design constraints for the ground software
  - Complete mission requirement flow-down
  - Early Agile process to inform requirements for components with higher uncertainty

Scaling to Meet Operation Demands

MOS Process	Scaling Approach
Hub & Node Eng. Analysis	(P) Use VISTA to view trending data from all S/C in one environment
Orbit Determination	(P) Process hub and node tracking and node relative ranging data in single ODTK filter. (A) Use heritage FDS platform (ref LADEE, STPSat-5, CYGNSS and Starling) and procedures, including scheduled job functionality (time-based or file delivery-based triggers).
Maneuver Planning	(A) Use heritage FDS platform and procedures
Activity Planning	(A) Use SPIFe's plan template functionality to create reusable subplans (A) Use SPIFe external script and plan fragment import functionality to replace manual plan creation
CMD Seq. Generation	(S) Tasks in Science Phase are repetitive, and nearly identical between nodes, allowing for the extensive use of sequence templates

Key: (P) parallelization, (A) utilization of automation platforms, and (S) exploiting simplifying features of HS's mission design.

Scaling to Meet Operation Demands

MOS Process	Scaling Approach
CMD Seq. Verification	(P) Hub PIL separate from node PIL (S) Simple node attitude profile doesn't require high- fidelity attitude simulation; rely on static flight rule checking code
RT T&C Monitoring	(P) MAESTRO for hub, individual instances of COSMOS for each node in virtualized environment (A) Use heritage MAESTRO functions for lights-out pass automation (for 2-hr tracking passes)
Approval Processes	(A) Use Confluence and Comala Workflows (ref. STPSat-5) for approval tracking and reminders
Inter-Process Exchanges	A) Use Confluence (with import export API) and Comala Workflows (STPSat-5) for product storage and notification; point-and-clicking and file system searching are greatly reduced

Key: (P) parallelization, (A) utilization of automation platforms, and (S) exploiting simplifying features of HS's mission design.